DNR Grant: "Describing connected fracture flow with pressure waves – oscillating flow interference testing"
PI: Michael Cardiff, University of Wisconsin-Madison, Department of Geoscience
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Project Objectives

The state of Wisconsin is blessed with abundant groundwater resources resulting from the thick, high-porosity and high-permeability sedimentary aquifers that underlie the state, as well as the humid climate it experiences. In managing the state's resources, a common modeling assumption is that these aquifers behave as traditional porous media, in which flow occurs dominantly through pores between individual sediment grains. Investigations in the state of Wisconsin by the WGNHS and other researchers (e.g., Runkel et al. 2006) have demonstrated that both laterally-continuous horizontal fractures and high-angle (near-vertical) fractures in these sedimentary units heavily influences their hydrogeologic behavior. For example, very fast travel times – between the surficial aquifer in Madison, WI and the deep sandstone aquifer tapped for water supply – that are not representative of porous media flow have been demonstrated recently by Bradbury et al. (2013) through analysis of virus transport. Understanding the hydraulic behavior of these fractures will thus be crucial for future modeling efforts that simulate flow and transport in the fractured rock aquifers underlying much of Wisconsin.

The research project for this grant performed field characterization of fractures at two sites in Dane County and Iowa County, Wisconsin where multiple observation wells were available. To characterize these fractures, we utilized a novel technology, multi-frequency oscillatory testing (in which a pumping well alternatingly injects and extracts fluid from the fractured interval). Specific objectives of the project were as follows:

1. To test the ability of cross-well Multi-frequency Oscillatory Hydraulic Testing (M-OHT) to produce measurable and analyzable signals at fractured rock sites where fracture connectivity has been previously inferred;
2. To use data from M-OHT testing to characterize the spatial “flow dimension” and hydraulic properties of fractures at each of the research sites; and
3. To develop an apparatus for performing single-well M-OHT testing, such that vertical connection between different fractured intervals could be assessed.

With regards to the second objective, a key planned benefit of the M-OHT testing is its ability to distinguish the “flow dimension” of a flow network. As illustrated in Figure 1, the arrangement and type of fracture flow can lead to water flow pathways that are either 1-D, 2-D, or 3-D in character. Especially as a fracture network is tested at multiple periods, mathematical models indicate that M-OHT testing should have different characteristic responses, depending on whether 1-D, 2-D, or 3-D flow is occurring, as the period of the testing changes.

Oscillatory Testing Background

Standard methods for performing aquifer or fracture characterization include constant-rate pumping tests, in which a well is pumped at a constant rate and head changes at surrounding monitoring wells are analyzed, and slug tests, in which a set volume is added to a well (inducing an instantaneous head change) and the return of the head change back to background conditions provides the data for analysis. Though less commonly performed in the literature, periodic tests represent another aquifer testing strategy that can provide valuable information for understanding flow properties. Periodic hydraulic testing represents any pumping strategy in which the flowrate at a pumping well is varied in a repeated fashion and the associated data (often, head changes at monitoring locations) are recorded and analyzed. Periodic testing may consist of an alternation between a pump being on and a pump being off, known as "pulse testing"(Johnson et al. 1966). Alternately, the pumping flowrate for a well may be varied in a periodic fashion (as initially suggested by Kuo 1972). The periodic testing approach to characterizing fractures has some significant practical advantages, relative to standard methods such as constant-rate pumping tests. For example, in a constant rate pumping test in which water is extracted from a fracture, the effective stress on the fracture may increase, leading to fracture compression that changes flow behavior. Alternately, if water is injected into the fracture, this action may cause dilation and more rapid flow. Using tests in which there is no net gain or loss of water from the fracture avoid this issue to some degree, by limiting overall pressure changes.

In this work, we utilized what we will refer to as oscillatory testing, in which the pumping rate at a well can be represented strictly as a cosinusoidal signal. In these oscillatory tests, pressure and flow within the tested well vary around a mean value of zero change, such that the there is no net extraction or injection of fluid into the well. Said mathematically, the pumping rate (fluid injected into the formation) for an oscillatory test can be represented as:

$$Q(t) = Q_{max} \cos\left(\frac{2\pi}{P} t\right)$$

where $Q\ m^3/s$ represents the flowrate at the well (positive extraction, negative injection), Q_{max} represents the peak flowrate obtained, $P\ (s)$ represents the period of injection, and $t\ (s)$ represents the time since the designated start of the experiment.

Unlike tests that are simply periodic or repeated in nature, a pumping test in which the flowrate follows a sinusoidal signal strictly has the following benefits:

- No water needs to be injected or extracted from the formation, which can limit testing costs (e.g., due to waste disposal);
- By limiting stimulation of the aquifer to a single period, data from these tests can be analyzed using a fast frequency-domain analytical or numerical models;
- By performing pumping at a known period, responses at monitoring wells can be decomposed such that only pressure changes at the given period are analyzed, making data treatment and noise / background trend reduction much simpler.

Responses to such oscillatory pumping will also consist of a sinusoidal / cosinusoidal signal at the given period P. The amplitude and the phase of the head changes seen at monitoring locations provide data for aquifer characterization which can then be used to infer the properties of the aquifer. As has been noted in previous investigations of aquifer characterization methods, a prominent “scale effect” is often seen in aquifers, whereby testing performed over short timescales (such as through slug tests) may show different effective aquifer parameters than those performed at longer timescales (such as from constant-rate pumping tests). The oscillatory testing methodology presents a useful way to interrogate this scale effect, as well, given that the period of testing can be varied intentionally. The remainder of this report describes the performance of oscillatory tests at two sites in Wisconsin, as well as analysis strategies employed.

Site Settings

Highway A Site (Iowa County, WI)

The first site at which M-OHT tests were performed is located in an unglaciated, rural area of Iowa County, WI (Figure 2). The site is located at a privately-owned abandoned quarry located directly north of County Highway A – approximately 5km east of Hollandale, WI. Two wells at the quarry, IW-512 and IW-529, were installed by the Wisconsin Geological and Natural History Survey (WGNHS) in 2007 and 2014, respectively. IW-512 is a 15.24 cm (6") borehole that is open to the surrounding formation from 24.4 m – 201 m below ground surface (bgs). IW-529 is a 5.1 cm (2") corehole located 9.1 m to the south of IW-512, and is open to the surrounding formation from 2.5 m – 177 m bgs (Figure 3). Core samples from drilling of well IW-529 are currently stored at the WGNHS Mt. Horeb Core Repository.

Unconsolidated surficial deposits at the Highway A site are less than 3 m thick. Below that, a locally standard progression of stratigraphic units is seen with increasing depth, starting with the Prairie Du Chien (primarily dolomite, ~41 m thick). Below this, the Trempealeau Group consists of the 8.5 m Jordan Formation sandstone followed by a 16 m thick dolomite. Next is the Tunnel City Group and Wonewoc formation – both sandstones, and 30 m and 56 m thick, respectively). The Eau Claire Formation, which contains prominent shale beds and is locally 22 m thick, is present below these units and represents a regional aquitard. Lastly, the Mt. Simon sandstone formation is found, which is below 177 m depth and thus only penetrated by IW-512.

Unit Well 7 Site (Dane County, WI)

The second site studied during this project is adjacent to Madison's municipal supply Unit Well 7 facility, located at the corner of Schlimgen Ave. and North Sherman Ave, immediately north of Shabazz City High School and Sherman Middle School (Figure 4). This site is located in Madison’s suburban “East Side” neighborhood. The municipal well itself is a 224.4 m deep high capacity well with an average annual pumping rate of around 300 million gallons (Madison Water Utility 2014). This municipal well is cased through the succession of unconsolidated deposits, the Tunnel City formation, and Wonewoc formation. It is open mainly to the underlying thick Mt. Simon formation, though a small portion of the well is also open to the overlying Eau Claire aquitard (Figure 5). A cluster of three monitoring wells are located to the south of the Unit Well 7 pump building, designated as MW-7S, MW-7D and MW-7VD – or “shallow”, “deep”, and “very deep”, respectively. These three wells were installed during prior research projects at the Unit Well 7 site. They each consist of polyvinyl chloride (PVC) casing, and are each screened over a small depth interval. MW7-S has a total depth of ~15 m and is screened only at the bottom 4.6 m of its length – it is thus open only to the Tunnel City group. MW7-D is approximately 30.4 m in total depth and is likewise only screened at the bottom 3 m, which spans both the Tunnel City and Wonewoc. Finally, MW7-VD is roughly 65.8 m total depth and is also screened only in the bottom 3m, which places the majority of the screened interval in the Wonewoc.

Methods

In our field testing, we performed M-OHT testing using the PneuSine, a custom-developed pneumatic testing system developed by HydroResolutions, LLC (http://hydroresolutions.com), which uses gas flow controllers to carefully manipulate total pressure and flow rates within a wellbore. The Pneusine system consists of a wellhead manifold cap and electronic equipment used to control air pressure oscillations within the wellbore. At the beginning of M-OHT testing, the manifold is placed on top of the well to be tested and sealed such that it is airtight. The manifold contains 4 ports: two cable pass-throughs allowing wired pressure transducers to be suspended within the wellbore, a gas (air) connection port, and an emergency pressure-release valve. Two pressure transducers are installed through the manifold, such that the first is above maximum water levels and measures ambient gas pressure, and the second is below well water levels, near the top of the well's screened interval. A gas line is connected to the gas port. The gas line and pressure transducer data cables are then connected to the Pneusine Data Acquisition and Control (DAQ) System, which is operated from a van at the land surface (see Figure 6). By measuring the difference in pressure between the lower and upper pressure transducers, the Pneusine DAQ system can effectively determine the water level within the well even as air pressure is modified by gas injection / extraction. The Pneusine control system uses this information to determine whether gas should be injected or extracted – using a pair of computer-controlled gas flow valves – in order to obtain "target" water levels at any point in time. The person operating the Pneusine system chooses a target waveform – for example, a sinusoid with 60 second period and 1m head amplitude. The Pneusine DAQ and control system then monitors well water levels and automatically adds or removes gas from the well, so that the measured water level matches the target waveform as closely as possible. Both the target and obtained waveforms are displayed to the user, so that the user can assess whether the system is effectively meeting the target waveform with reasonable fidelity. In a case where any gas control issues arise, the air pressure can be manually vented from the well using the emergency valve on top of the wellhead manifold. In terms of adding gas pressure to the well, either surficial tanks or air compressors can be used as a source for gas control. For all testing described in this work, a DeWalt air compressor was used as the source for gas injection.

When designing oscillatory pumping tests, key parameters that must be chosen are the total cycle volume (the volume injected / extracted per period of oscillation) and the period of oscillation. With regard to the former, the Pneusine is primarily constrained by the height of the water level relative to the height of the top of the screened interval in a well. As air pressure is added to the sealed-off well, the water level must be kept above the top of the screened interval to avoid pushing air into the surrounding formation. Thus, the total volume that can be oscillated by the Pneusine is equal to the cross-sectional area of the casing multiplied by the available unscreened length of casing (from static water level to top of screen). With regard to the latter parameter – the oscillation period – the Pneusine is largely controlled by how quickly the computerized gas injection / extraction valves are able to meet desired pressures. In practice, Pneusine flow control was less stable below a period of ~10 seconds.

Data Collected

A diagram showing the field setup at the land surface at Highway A is shown in Figure 7. At the Highway A site where both wells are fully screened, individual depths were tested by installing packers with a 1 m open interval at the desired depth. In IW-512, the open interval of the packers was hydraulically connected to the packer riser pipe, on which the Pneusine manifold was installed. This allowed pressure to be oscillated by the Pneusine within a discrete depth interval only. At IW-529, a similar assembly was installed, again with a 1 m open interval connected to the packer riser pipe. By installing a pressure transducer within the riser, pressure changes at the designated depth interval could be measured. Other pressure transducers were utilized in both wells in order to measure pressure changes above and below each set of packers (see Figure 8). Several pairs of intervals were tested at the Highway A site, as indicated in Table 1. In the first and last testing setups, both packers were set at the depth associated with a prominent horizontal fracture (32m bgs for the upper fracture, and 48m bgs for the lower fracture). In the other two testing setups, connection was assessed between the upper fractured interval and the formation rock (Cross interval 1) and between the upper fractured interval and the lower fractured interval (Cross Interval 2). The series of tests performed, including start / end times and oscillation periods, is shown in Table 2.

The field setup at the Unit Well 7 site was much simpler, given the availability of power supplies and a lack of need for packer equipment. The surface setup during testing is shown in Figure 9. At the Unit Well 7 site, the three monitoring wells available were already screened over a small interval of the aquifer and thus packers were not necessary. For these tests, the Pneusine system was simply attached to the top of one of the wells, and pressure was monitored at the remaining two wells by installing pressure transducers. Two testing arrangements were used at the Unit Well 7 site, in which MW-7D and MW-7VD were used as pumping locations, and the remaining wells were monitored for pressure changes. The two setups used for testing are shown in Figure 10. The complete list of tests performed at this site is shown in Table 3. Again, we note that MW7-S was not tested for pumping because of the small head space available for oscillation (between ambient water levels and the top of the well screen) at this well.

Data Analysis

To analyze data from oscillatory tests, measurements of flowrate at the pumping well are recorded and modeled as a sinusoid with a specified amplitude and phase. Similarly, measurements of pressure change at monitoring wells are also fit to a sinusoidal signal with a given amplitude and phase. The ratio of the amplitudes between these two signals and the phase delay between these two signals can be used to perform parameter estimation for the aquifer material between the two locations. In our case, the analysis of these signals provides an estimate of the fracture diffusivity (D), i.e. the ratio of fracture transmissivity (T) to storativity (S). The mathematical details of solutions for the groundwater flow equation during oscillatory pumping for 1-D, 2-D, and 3-D flow geometries can be found in Cardiff and Sayler (2016). The end result of these mathematical formulations, however, is that if a diffusivity value is specified for a fracture or fracture network, the amplitude and phase of signals at a given radial distance (r) can be determined using the formulas found in Table 4. During parameter estimation, observed amplitudes and phases of pressure signals can be fit by altering the value of fracture diffusivity until acceptable fit is obtained. Though occasionally measurements of pressure at monitoring wells contained spurious signals, identification of the stimulation from the pumping well was always easy, given the known period of pumping. For example, testing results at Unit Well 7 were sometimes over-printed with large background signals caused by changes to the pumping rate of the Unit Well. An example of this behavior (and the recovery of oscillatory signals) is shown in Figure 11. Once the testing signal was separated from other spurious background signals, the sinusoid at the given period could be fit with the analytical models described. Examples of data fitting to raw (unprocessed) field data across a range of periods are shown in Figure 12.

Results from Highway A Data Analysis

Data from the Highway A site was fit across a range of periods using both amplitude ratios (ratio of pumping well flowrates to head changes) and phase delays (difference between phase at pumping well and phase at monitoring well). The parameter estimates obtained using 1-D, 2-D, and 3-D flow geometry assumptions are shown in Figure 13 for the upper fractured interval, and in Figure 14 for the lower fractured interval. In all cases, two different signal metrics were used to estimate diffusivity. First, the ratio between the pumping rate magnitude at the stimulation well and the head oscillations at the monitoring well (amplitude ratio) can provide an estimate of diffusivity, which are displayed as the square boxes. Another estimate of diffusivity can be obtained by analyzing the phase lag between the pumping rate in the pumping well and the head change in the monitoring well, which is displayed as filled circles. By using both of these parameter estimation approaches, we can assess whether the data is internally consistent for a particular flow dimension.

As seen in Figure 13, for the upper fractured interval the 1-D and 3-D flow models were not able to obtain consistent parameter estimates when different signal metrics for the data were fit. In contrast, the 2-D model obtained consistent parameter estimates whether amplitude ratios or phase lags were fit. Multiple tests performed at the same period also showed consistent parameter estimates obtained throughout (i.e., parameter estimates at individual periods are tightly clustered), suggesting that the raw data was of high quality. One behavior that is seen across conceptual models is an apparent “period-dependence” in fracture hydraulic diffusivity estimates. In general, we see diffusivity estimates of 1 – 10 m^2/s, but a general trend of slight decreases in obtained diffusivity estimates as the period of oscillatory pumping increases is seen. This period-dependent diffusivity has been observed by other researchers during testing on fractured rock, though the source of this period-dependence is still a subject of current research (Becker and Guiltinan 2010, Guiltinan and Becker 2015). One likely cause for this period dependence is the fact that at larger periods of oscillation, the oscillating pumping test is sensitive to different heterogeneities, as it effectively senses larger volumes of the surrounding aquifer (see, e.g., the sensitivity maps for different testing periods derived by Cardiff et al. 2013).

Parameter estimates were much more variable for the lower fractured interval at Highway A (Figure 14). Additionally, multiple tests performed at the same period had a wider scatter in parameter estimates, suggesting less reliable experimental data, possibly due to low-magnitude signals. In the case of the lower fractured interval, we believe that the underlying modeling assumption of a fracture of infinite lateral extent is not correct for this fractured interval. Additional modeling in which a fracture with a boundary was used (e.g. due to pinching) led to more consistent parameter estimates (see Sayler et al. 2017-in press).

Finally, none of the “cross-interval” tests performed at Highway A produced signal propagation that was measurable across the range of periods investigated. Together, these results provide evidence for the following:

- The fractured intervals at Highway A are the dominant flow features contributing to local reservoir transmissivity. Flow in the surrounding host rock is likely slow, with limited signal propagation into this rock

- Given the ability of 2-D models to fit data most acceptably, and the lack of signal propagation between “cross-interval” tests, it is likely that fractures at Highway A are quasi-planar, horizontal features with limited vertical connectivity between fractured intervals.
- Variability of fracture parameter estimates across a range of testing periods suggests that the fractures are displaying “period dependence” (likely associated with within-plane fracture heterogeneity and slow-flow “pinched” regions), similar to behavior observed by other researchers.

Results from Unit Well 7 Data Analysis

Diffusivity estimates from the Unit Well 7 site were performed in the same manner described above for the Highway A site. Similarly, Figure 15 shows the hydraulic diffusivity estimates obtained when utilizing 1-D, 2-D and 3-D conceptual models for flow. Several tests were performed at some of the testing periods, and the limited scatter in parameter estimates suggest that this data (and the associated parameter estimates) are of high quality. Though the trend is less striking than in the case of Highway A, the 2-D conceptual model appears to result in the most consistent set of parameter estimates, when both phase lag and amplitude ratio analyses are performed. We thus infer that the connectivity between MW7-D and MW7-VD is dominated by a 2-D flow feature (such as a high-angle fracture). This result is consistent with analyses by Gellasch et al. (2013), who used borehole logs to infer existence of high-angle fractures and possible connectivity between shallower and deeper monitoring wells. One question about the connectivity at the Unit Well 7 site is whether it has been induced by human disturbances, such as 1-D flow along poorly-grouted casing. Our analyses suggest that this is unlikely, given that the periodic test results were far more consistent with a 2-D than a 1-D flow geometry. As before, the parameter estimates from Unit Well 7 show an unexplained apparent period-dependence, with diffusivity decreasing as a function of testing period. We believe that this period-dependence may be associated with within-plane fracture heterogeneity – a subject of future research that is being investigated in a currently funded NSF-CAREER Award (NSF-EAR Award # 1654649).

Equipment Design

The testing performed at both Highway A and Unit Well 7 suggests that oscillatory hydraulic testing provides a useful method for examining aquifer properties, especially in "noisy" environments where hydraulic forcings other than the planned testing may be present. However, a key drawback of the setups used in the current field campaigns is that at least 2 wells (a pumping well, and a monitoring well) must be used to assess fracture connectivity. High angle fractures, as well, present a particularly difficult target as they are more sparsely sampled by vertical monitoring wells. The ability to consistently use oscillatory pumping tests to assess the connectivity between high-angle fractures and other fractures within a network would be a valuable tool for practicing hydrogeologists.

To address the need for a more practical and useful tool that could be deployed in environments where only one well was available, we have developed a design for a single-well oscillatory testing system that could be implemented for future testing. Shown in Figure 16, the testing design consists of: 1) A straddle packer assembly on riser pipes which is suspended down to the fractured interval to be tested (labeled as "zone 4"); 2) a secondary straddle packer on a thicker pipe section which slips over the riser pipe for the other assembly, isolating a second zone within the well (labeled as “zone 2”), and allowing for an assessment of connectivity between zone 4 and zone 2; 3) A manifold and Pneusine testing apparatus, which is connected to the riser pipe.

Since all hydraulic tests are reciprocal (i.e., the response and parameter estimates are guaranteed to be the same if pumping and monitoring locations are reversed), this testing setup relies on a case in which the pumping interval is always the lower of the two tested intervals. The advantage of this approach, from the perspective of pneumatic testing, is that the lower interval will generally have a greater water column distance between the well screen and the top of the well water level. This means that the pneumatic gas-injection system will be able to push a larger column of water into the formation during stimulation, without risk of pushing gas into the well screen.

Conclusions & Future Work

This work demonstrated the use of multi-period oscillatory pumping tests for characterizing connectivity and fracture parameters within fractured sedimentary rock aquifers. Using this approach, we were able to obtain clearly measurable signals even in highly “noisy” environments such as the Unit Well 7 site, where the signal due to testing is much smaller than signals due to other background activity. In addition, for both the upper interval of the Highway A site, and the Unit Well 7 site, we demonstrated that oscillatory testing allows the assessment of multiple conceptual models for flow and suggests that both of these locations are dominated by 2-D fracture sets, rather than by 1-D fracture “channels” or highly-interconnected 3-D fracture networks.

Future access to the Highway A site is likely limited, due to a transfer in the land ownership. However, additional testing may be possible at other Unit Wells, or near other municipal wells in Wisconsin. In addition, our research group is currently working to develop a new research site near the Token Creek Springs Preserve, which would allow the assessment of cross-well and single-well oscillatory hydraulic testing methods for characterizing this fracture-dominated environment. We hope to implement our planned single-well oscillatory testing design at this field site, in addition to cross-well testing that will assess fracture interconnectivity

Figures

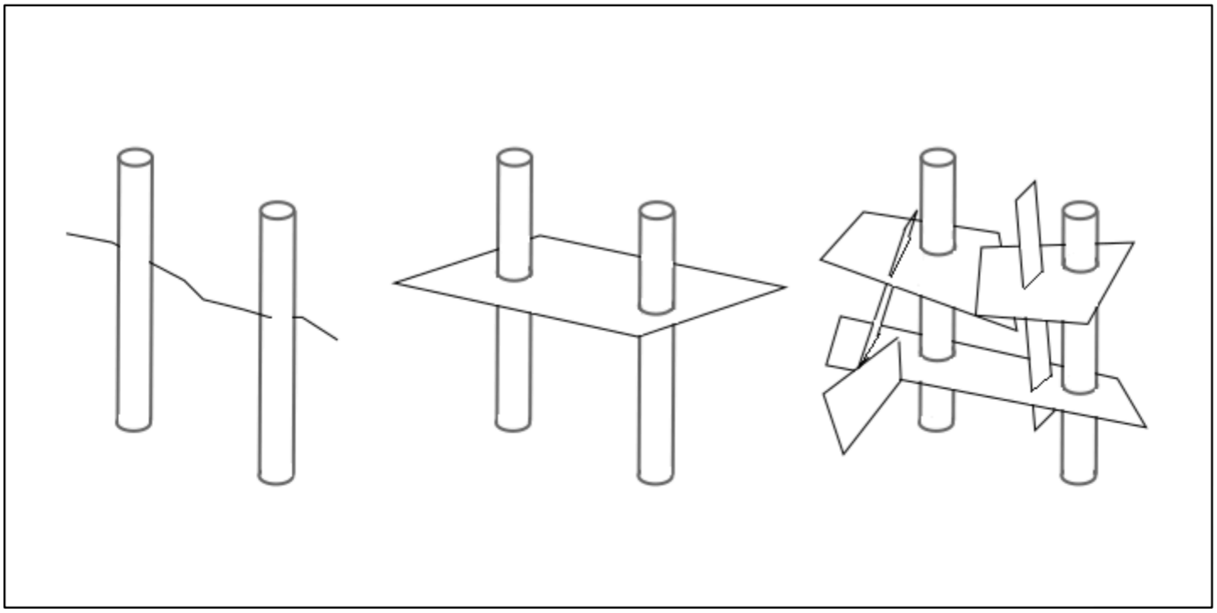


Figure 1: Flow geometry resulting from different "flow dimensions" of fracture geometry. Left: A single channel within a fracture plane may be especially high-aperture, allowing essentially one-dimensional flow between two monitoring wells; Center: A fracture plane with roughly uniform aperture could provide two-dimensional flow between two wells; Right: In the case of a highly fractured porous media, the interconnected fracture network allows three-dimensional flow.

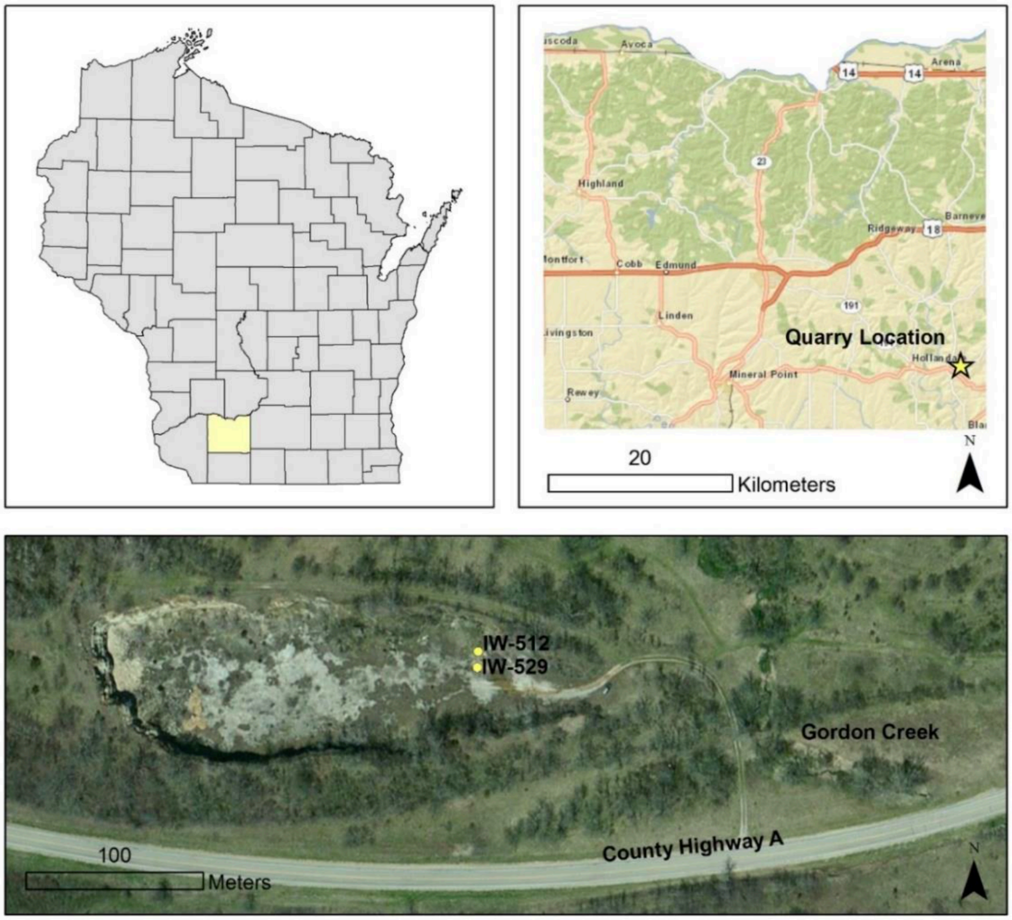


Figure 2: Location of Highway A research site in Iowa County, WI. Locations of monitoring wells are marked on bottom figure.

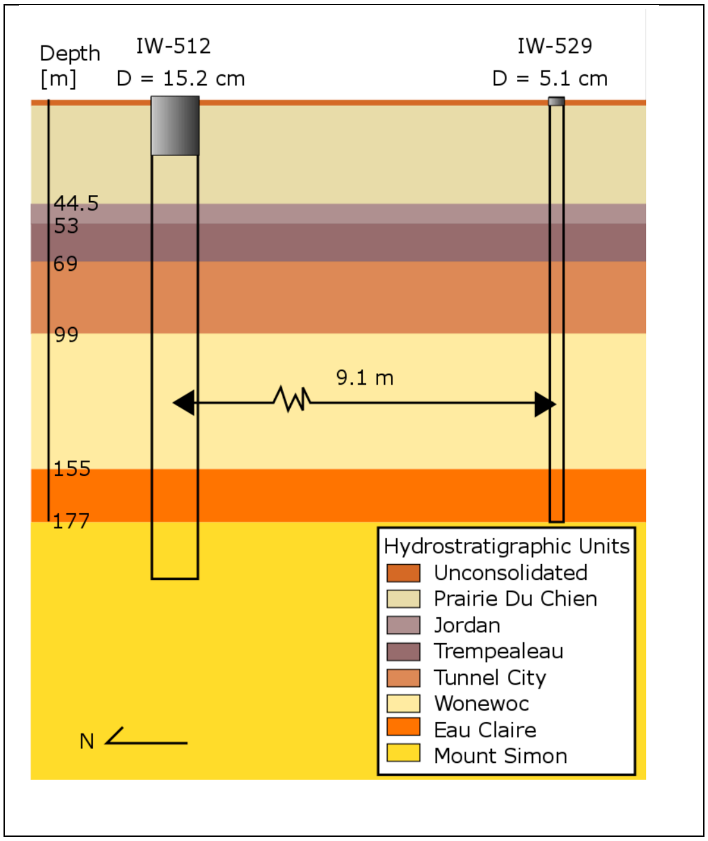


Figure 3: Site setup and stratigraphy at Highway A site.

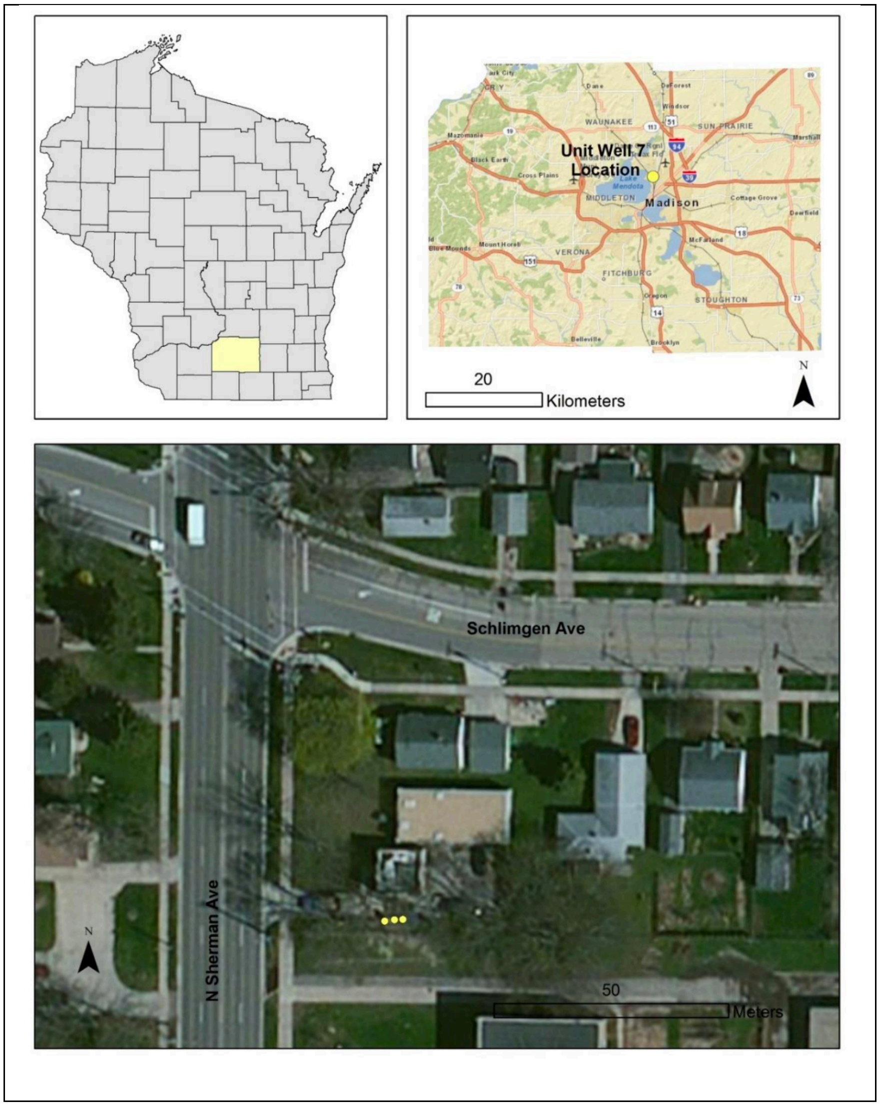


Figure 4: Location of the Unit Well 7 Field Site in Dane County, WI. Locations of monitoring wells are indicated in yellow on bottom figure.

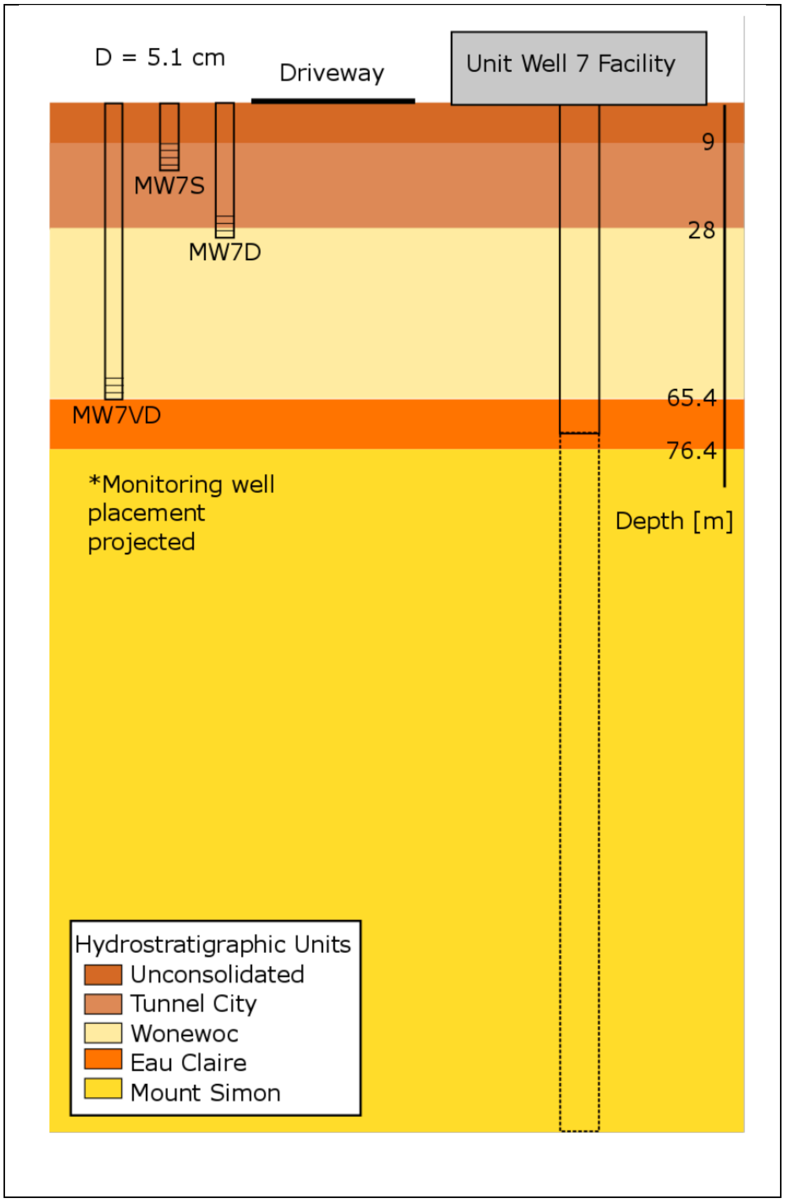


Figure 5: Monitoring well setup and site stratigraphy at Unit Well 7 site.

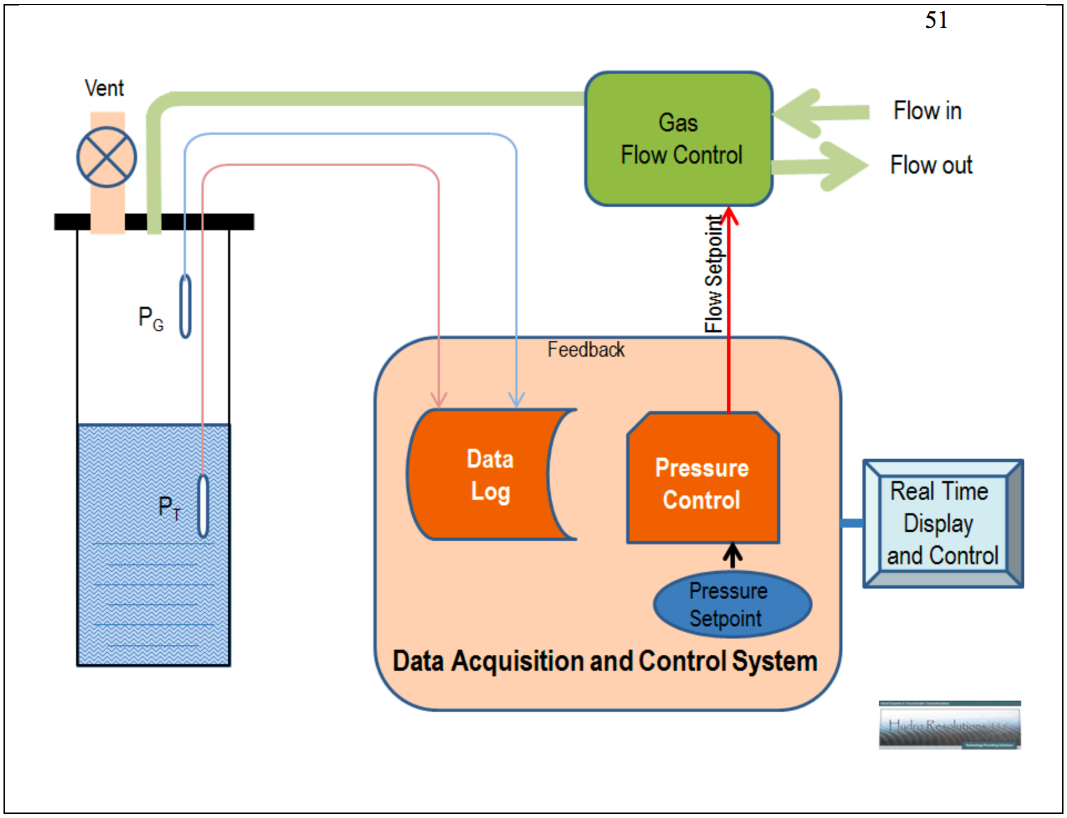


Figure 6: Pneusine equipment design diagram (courtesy of HydroResolutions).

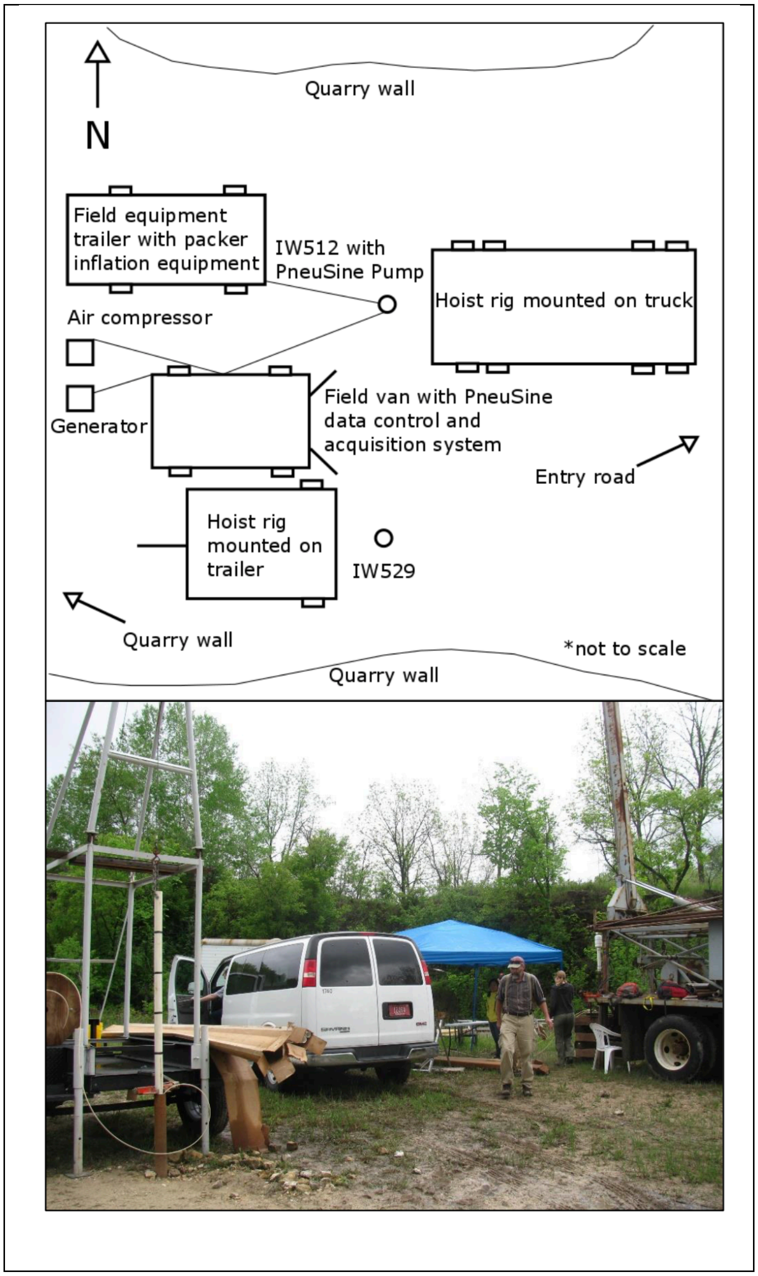


Figure 7: Field setup at land surface for the Highway A site.

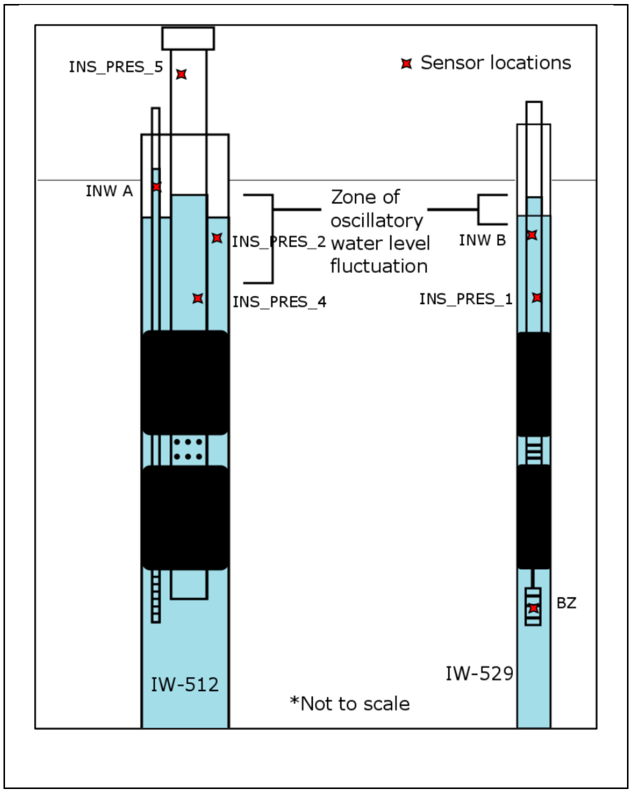


Figure 8: Testing installation, with packer assembly, at Highway A site. Cap at the top of well IW-512 represents the Pneusine manifold system.

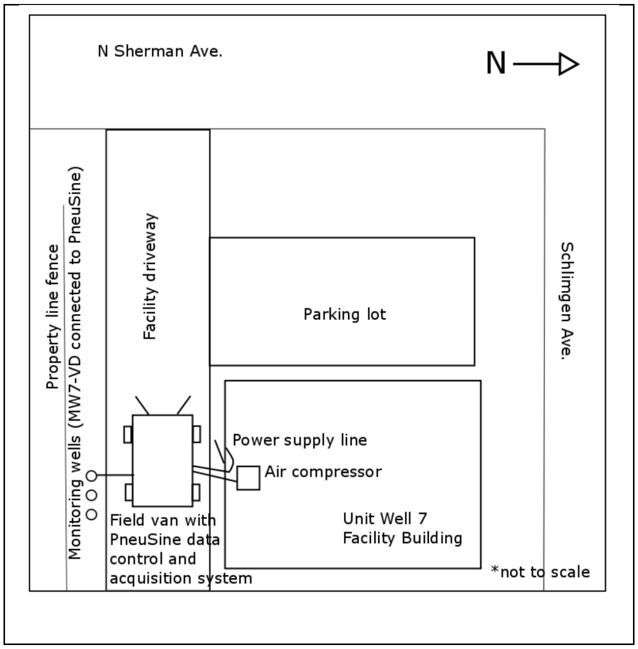


Figure 9: Surface setup for testing at Unit Well 7 site

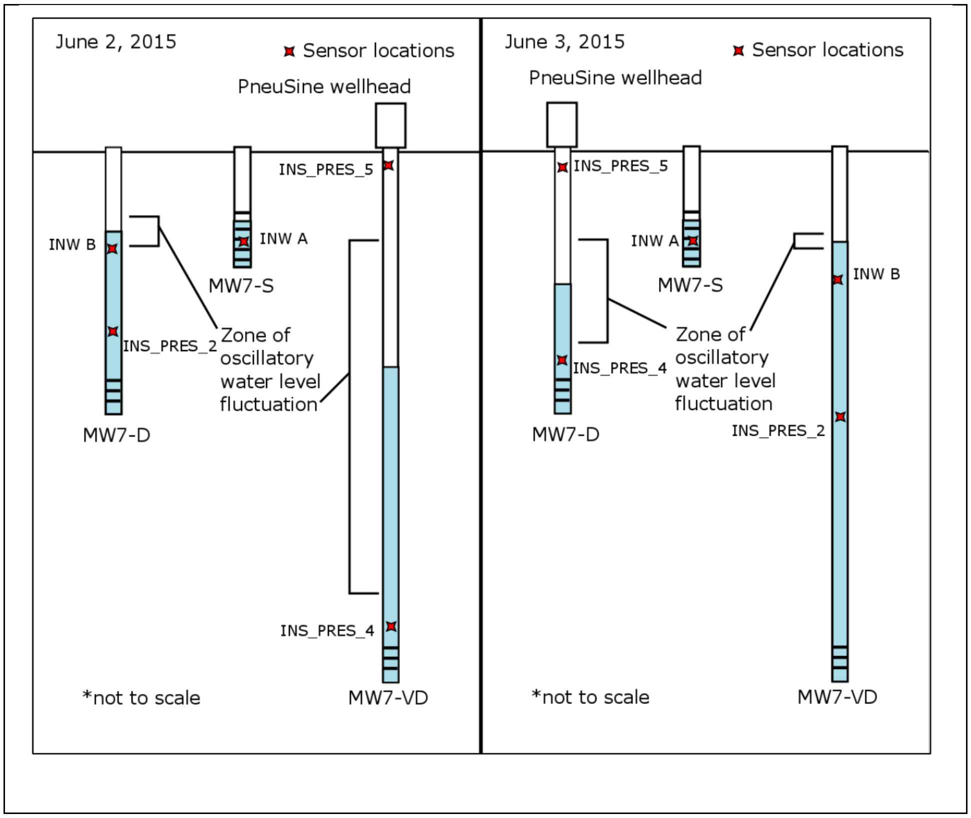


Figure 10: Setups for testing of wells used at the Unit Well 7 site.

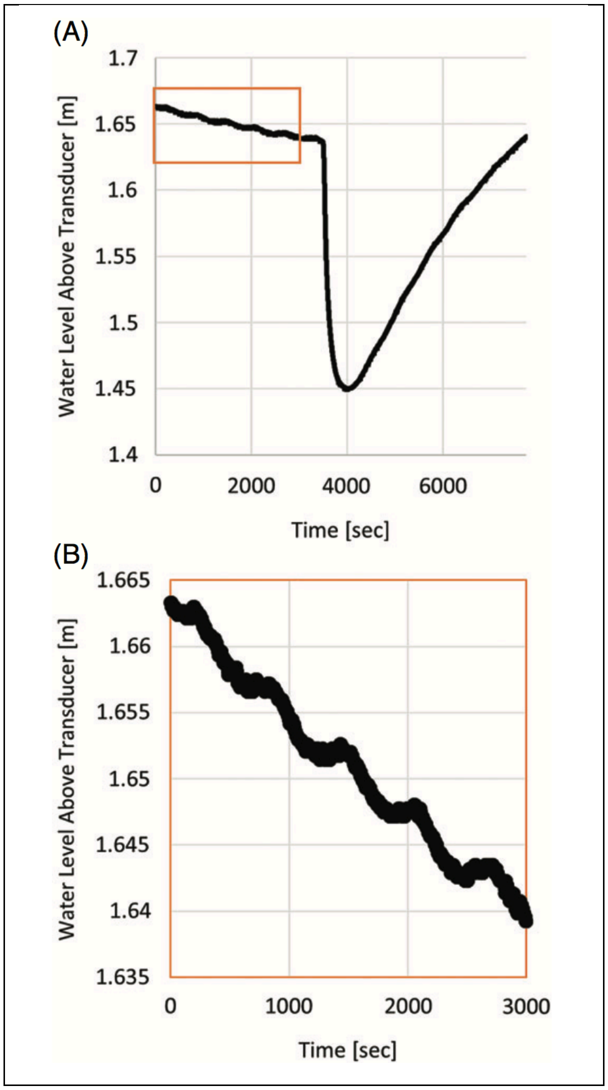


Figure 11: Head changes recorded by pressure transducers at the Unit Well 7 site. (A) raw signal during a time when the flow rate at the Unit Well was changing. (B) Zoom-in on period of relatively stable pumping rates, showing pressure oscillations at the testing period of 600 seconds.

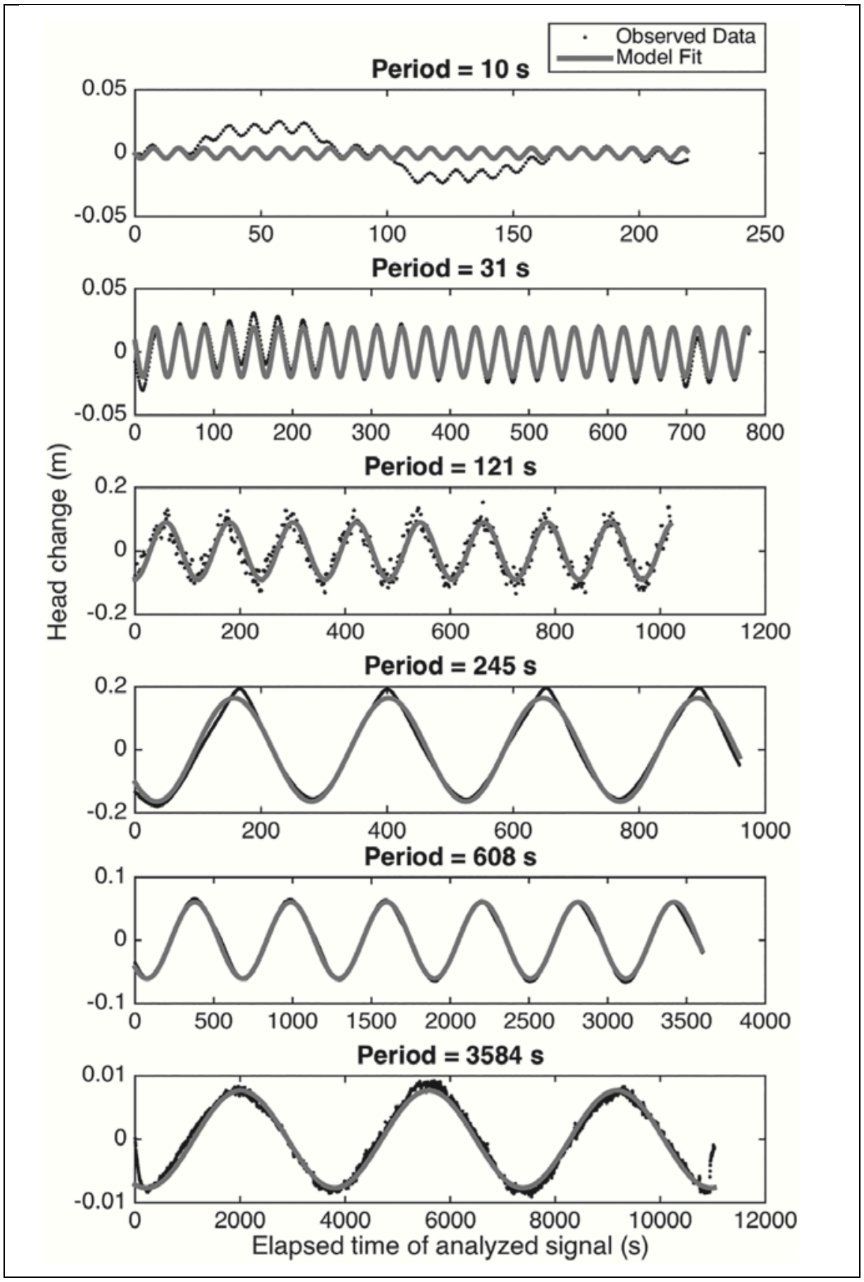


Figure 12: Examples of data fit from oscillatory testing parameter estimation (Highway A site, upper interval data fitting)

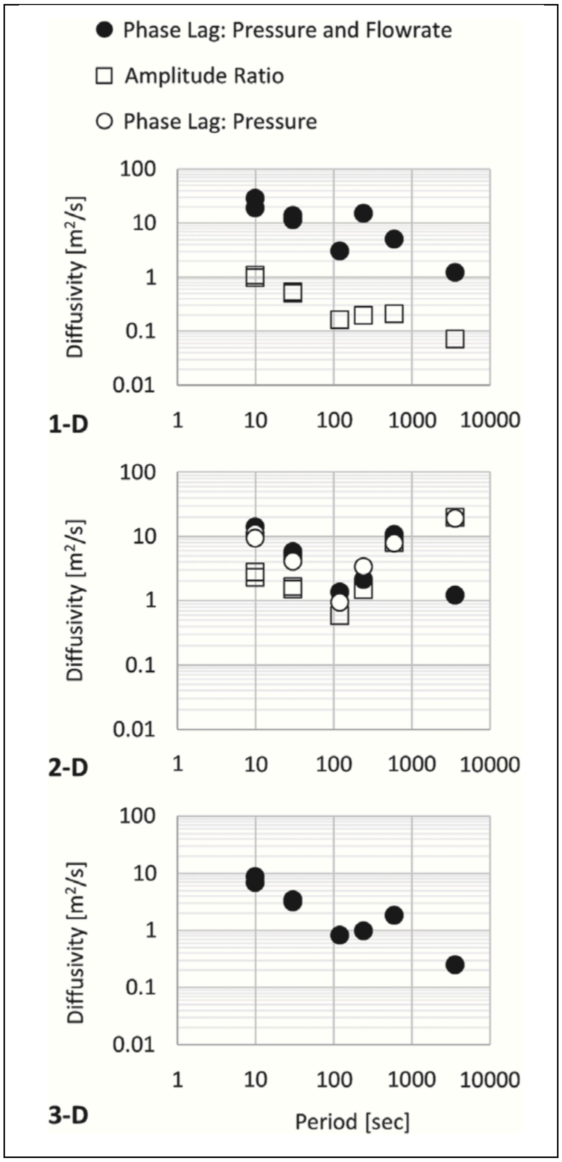


Figure 13: Estimates of fracture hydraulic diffusivity for Highway A site, upper fractured interval, assuming 1-D, 2-D and 3-D flow geometries. Different symbols correspond to different methods for processing (obtaining signal metrics) and analyzing of OHT data. In cases where symbols are not displayed, the signal metrics could not be fit acceptably.

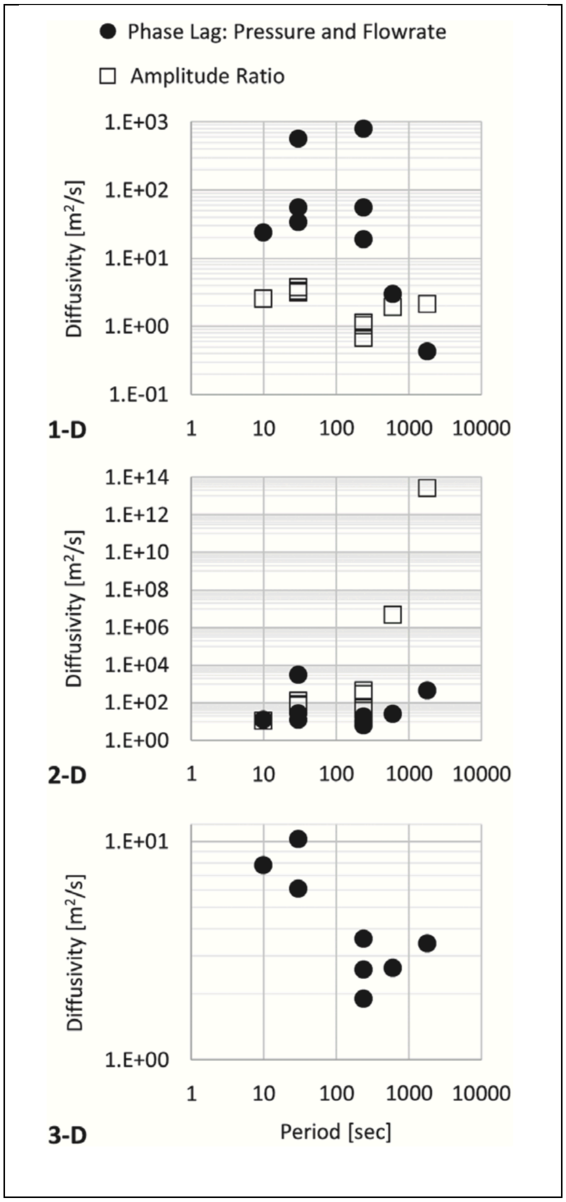


Figure 14: Estimates of fracture hydraulic diffusivity for Highway A site, lower fractured interval, assuming 1-D, 2-D, and 3-D flow geometries.

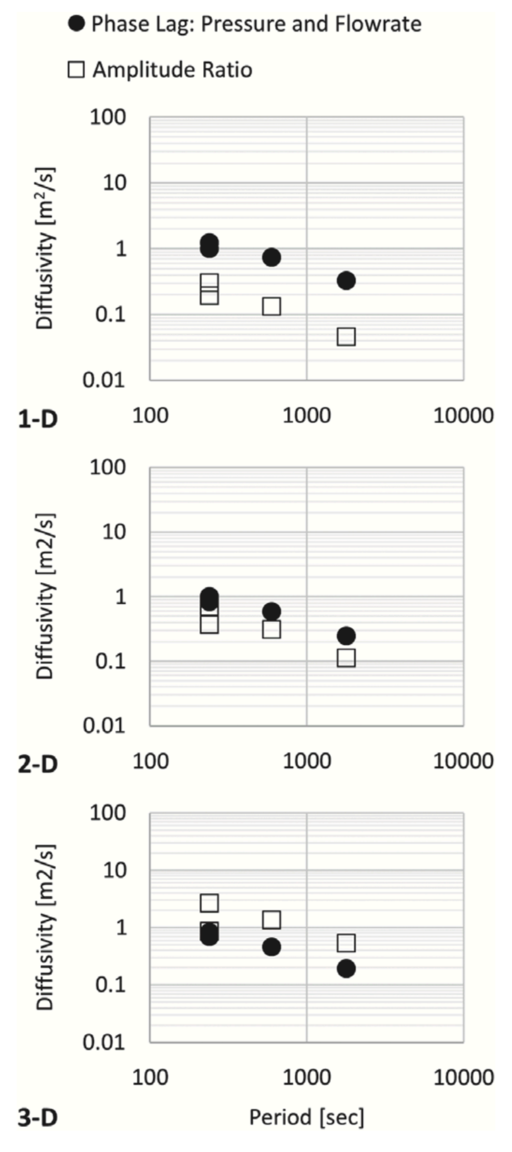
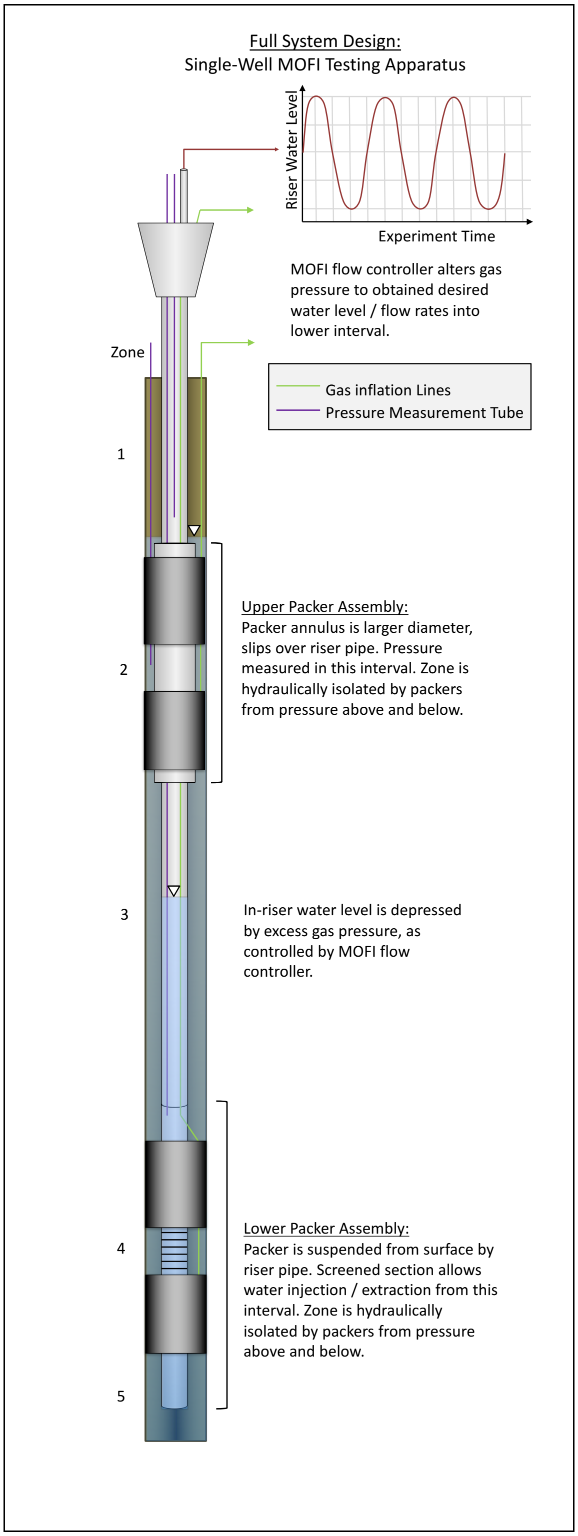


Figure 15: Diffusivity estimates from Unit Well 7 site, when using 1-D, 2-D, and 3-D conceptual models



MOFI flow controller alters gas pressure to obtained desired water level / flow rates into lower interval.

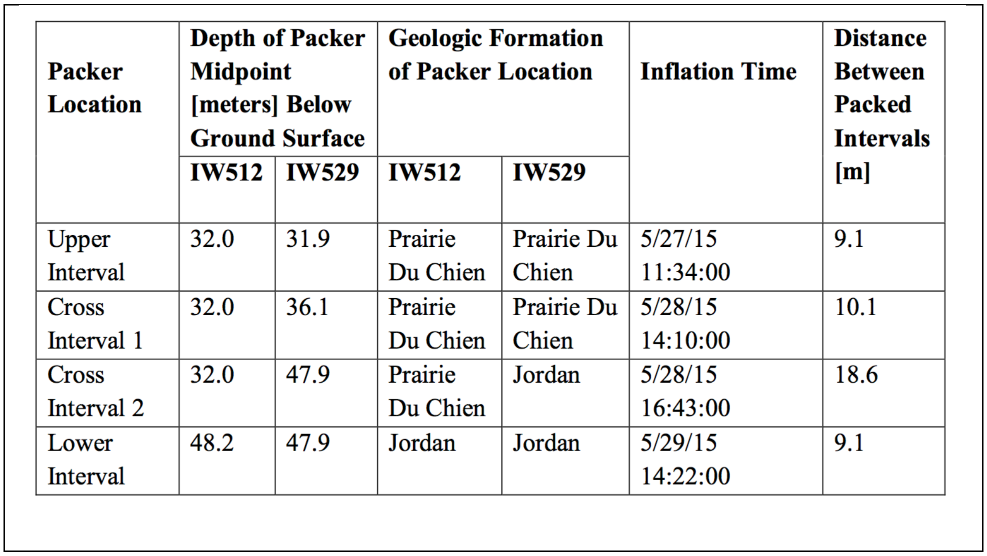
Upper Packer Assembly: Packer annulus is larger diameter, slips over riser pipe. Pressure measured in this interval. Zone is hydraulically isolated by packers from pressure above and below.

In-riser water level is depressed by excess gas pressure, as controlled by MOFI flow controller.

Lower Packer Assembly: Packer is suspended from surface by riser pipe. Screened section allows water injection / extraction from this interval. Zone is hydraulically isolated by packers from pressure above and below.

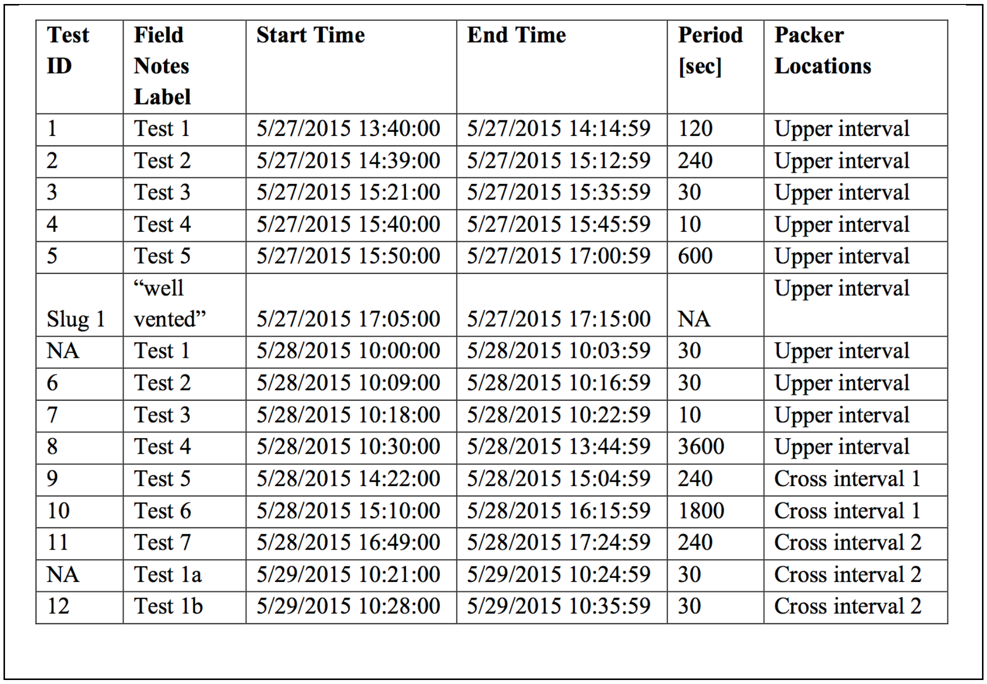
Figure 16: Design for single-well oscillatory testing setup

Tables



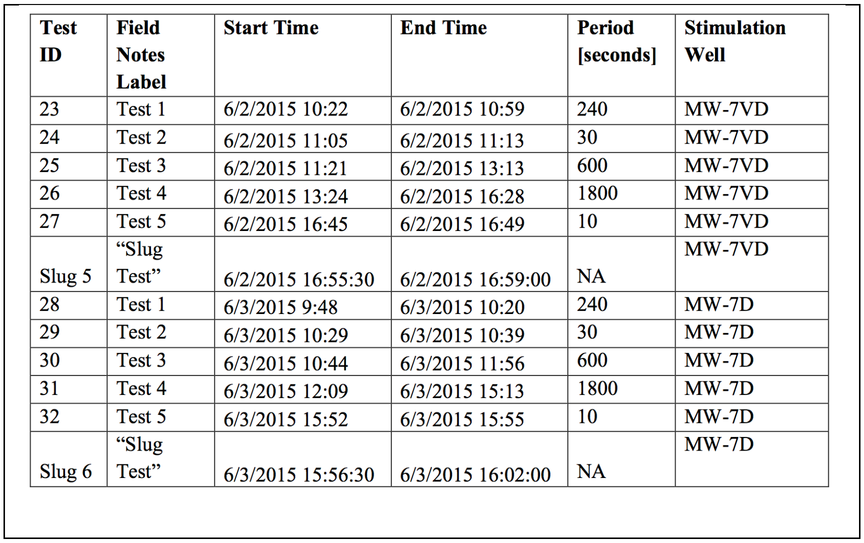
Packer Location	**Depth of Packer Midpoint [meters] Below Ground Surface**		**Geologic Formation of Packer Location**		**Inflation Time**	**Distance Between Packed Intervals [m]**
	IW512	**IW529**	**IW512**	**IW529**		
Upper Interval	32.0	31.9	Prairie Du Chien	Prairie Du Chien	5/27/15 11:34:00	9.1
Cross Interval 1	32.0	36.1	Prairie Du Chien	Prairie Du Chien	5/28/15 14:10:00	10.1
Cross Interval 2	32.0	47.9	Prairie Du Chien	Jordan	5/28/15 16:43:00	18.6
Lower Interval	48.2	47.9	Jordan	Jordan	5/29/15 14:22:00	9.1

Table 1: Testing arrangements for different tests performed at the Highway A site using packer assemblies.



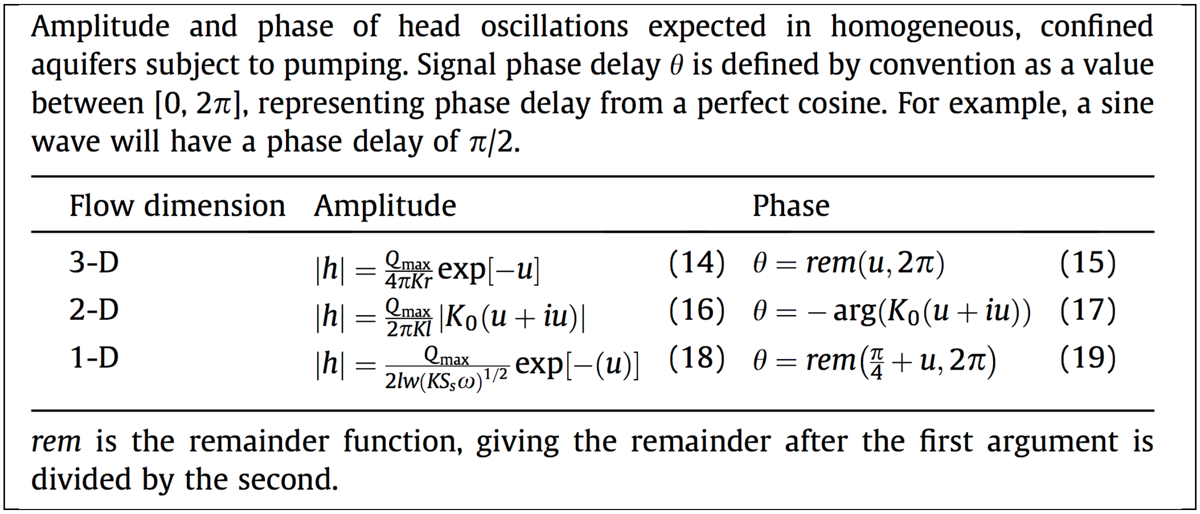
Test ID	Field Notes Label	Start Time	End Time	Period [sec]	Packer Locations
1	Test 1	5/27/2015 13:40:00	5/27/2015 14:14:59	120	Upper interval
2	Test 2	5/27/2015 14:39:00	5/27/2015 15:12:59	240	Upper interval
3	Test 3	5/27/2015 15:21:00	5/27/2015 15:35:59	30	Upper interval
4	Test 4	5/27/2015 15:40:00	5/27/2015 15:45:59	10	Upper interval
5	Test 5	5/27/2015 15:50:00	5/27/2015 17:00:59	600	Upper interval
Slug 1	“well vented”	5/27/2015 17:05:00	5/27/2015 17:15:00	NA	Upper interval
NA	Test 1	5/28/2015 10:00:00	5/28/2015 10:03:59	30	Upper interval
6	Test 2	5/28/2015 10:09:00	5/28/2015 10:16:59	30	Upper interval
7	Test 3	5/28/2015 10:18:00	5/28/2015 10:22:59	10	Upper interval
8	Test 4	5/28/2015 10:30:00	5/28/2015 13:44:59	3600	Upper interval
9	Test 5	5/28/2015 14:22:00	5/28/2015 15:04:59	240	Cross interval 1
10	Test 6	5/28/2015 15:10:00	5/28/2015 16:15:59	1800	Cross interval 1
11	Test 7	5/28/2015 16:49:00	5/28/2015 17:24:59	240	Cross interval 2
NA	Test 1a	5/29/2015 10:21:00	5/29/2015 10:24:59	30	Cross interval 2
12	Test 1b	5/29/2015 10:28:00	5/29/2015 10:35:59	30	Cross interval 2

Table 2: Series of tests carried out at Highway A site.



Test ID	**Field Notes Label**	**Start Time**	**End Time**	**Period [seconds]**	**Stimulation Well**
23	Test 1	6/2/2015 10:22	6/2/2015 10:59	240	MW-7VD
24	Test 2	6/2/2015 11:05	6/2/2015 11:13	30	MW-7VD
25	Test 3	6/2/2015 11:21	6/2/2015 13:13	600	MW-7VD
26	Test 4	6/2/2015 13:24	6/2/2015 16:28	1800	MW-7VD
27	Test 5	6/2/2015 16:45	6/2/2015 16:49	10	MW-7VD
Slug 5	“Slug Test”	6/2/2015 16:55:30	6/2/2015 16:59:00	NA	MW-7VD
28	Test 1	6/3/2015 9:48	6/3/2015 10:20	240	MW-7D
29	Test 2	6/3/2015 10:29	6/3/2015 10:39	30	MW-7D
30	Test 3	6/3/2015 10:44	6/3/2015 11:56	600	MW-7D
31	Test 4	6/3/2015 12:09	6/3/2015 15:13	1800	MW-7D
32	Test 5	6/3/2015 15:52	6/3/2015 15:55	10	MW-7D
Slug 6	“Slug Test”	6/3/2015 15:56:30	6/3/2015 16:02:00	NA	MW-7D

Table 3: Tests carried out at the Unit Well 7 site. For these tests, all non-pumping wells were monitored with pressure transducers for signal propagation.



Amplitude and phase of head oscillations expected in homogeneous, confined aquifers subject to pumping. Signal phase delay θ is defined by convention as a value between [0, 2π], representing phase delay from a perfect cosine. For example, a sine wave will have a phase delay of $\pi/2$.

Flow dimension	Amplitude		Phase	
3-D	$\lvert h\rvert = \frac{Q_{\max}}{4\pi Kr}\exp[-u]$	(14)	$\theta = rem(u, 2\pi)$	(15)
2-D	$\lvert h\rvert = \frac{Q_{\max}}{2\pi Kl}\lvert K_0(u+iu)\rvert$	(16)	$\theta = -\arg(K_0(u+iu))$	(17)
1-D	$\lvert h\rvert = \frac{Q_{\max}}{2lw(KS_s\omega)^{1/2}}\exp[-(u)]$	(18)	$\theta = rem(\frac{\pi}{4}+u, 2\pi)$	(19)

rem is the remainder function, giving the remainder after the first argument is divided by the second.

Table 4: Expected amplitude and phase of head signal obtained at a monitoring well. Here Q_{max} represents the peak flowrate at the pumping well, K represents unit hydraulic conductivity S_s specific storage, l represents the thickness of a 2-D flow geometry (e.g., fracture aperture), and w represents the width of a 1-D flow channel (e.g., fracture channel width), and $\omega = \frac{2\pi}{P}$, is the oscillation frequency. All solutions are given in terms of the dimensionless quantity $u = ((\omega S_s\, r^2)/2K)^{1/2}$

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