ANALYSIS OF EARLY-TIME OSCILLATORY AQUIFER RESPONSE

Daniel A. Giffin and David S. Ward

GeoTrans, Inc.
Herndon, Virginia

ABSTRACT

Analysis of the oscillatory head response at observation wells obtained during the first minute of aquifer testing provided adequate data to hydraulically characterize a highly transmissive site in west-central Florida. A new analysis technique provides an independent means of deriving aquifer transmissivity based on the oscillatory deviations from the classic Theis theory. The method allows substantial cost savings in applications where long-term aquifer characteristics such as leakance are not required. With the use of pressure transducers, hundreds of head measurements were obtained during the first few minutes of a 180 gpm test. Within seconds, observation wells located within a few hundred feet of the pumped well responded in an oscillatory fashion. The oscillations damped in minutes and displayed amplitudes similar to the ultimate 24-hour responses of almost a foot of drawdown. Interpretation of the early-time oscillations is achieved by applying a Theis filter. The decaying sinusoidal deviations are evaluated using the method derived by van der Kamp for underdamped slug testing. The results obtained by this method (10,000 to 20,000 feet^2/day) are consistent with conventional interpretation of the aquifer test during the drawdown and recovery periods. In addition, 10-minute underdamped slug tests were found to be consistent in deriving a net transmissivity at the site where significant solution features have been identified via independent surface geophysics and fracture trace analysis. While the interpretation of early-time oscillatory aquifer response provides an effective means of characterizing transmissivity, aquifer testing may need to be conducted for several hours or days to determine leakance or boundary effects.

INTRODUCTION

During an aquifer test in the limestone of the Floridan aquifer in Northern West Central Florida, significant oscillatory water levels were measured at observation wells. The oscillations were dampened within the first minute of drawdown as well as during recovery. Many investigators simply ignore these early time data. In the past these oscillations have been attributed to many different causes including: cyclic behavior of the pumping mechanism, turbulence from pump startup, storage effects in the pumped well, and inertial effects in the aquifer. In reviewing the conventional aquifer and slug test interpretations, a novel approach was devised which addresses these oscillations. The technique, based on existing theories, is to filter the classical Theis response and analyze the decaying sinusoidal response.

Recently, a more rigorous mathematical analysis of oscillatory responses at observation wells was developed (Shapiro, 1988). Aquifer tests conducted in a fractured dolomite in northeastern Illinois were analyzed. The solution was obtained by numerical inversion of the Laplace transformation governing fluid movement in observation wells and the aquifer.

BACKGROUND

A field investigation was designed and conducted to collect data in support of the development of a dual-porosity and discrete fracture groundwater flow model. The regional model covers a six country area (GeoTrans, 1988). This study was composed of the following tasks:

- Selection of hydrologic test sites
- Fracture-trace analysis using aerial photos, maps and surface geophysics
- Aquifer test plan
- Installation of monitor wells
- Pre-test measurement of water levels and slug testing
- Aquifer test

The emphasis of the study was to better characterize the flow of groundwater through the karst limestone of the Floridan Aquifer in the Northern Basin.

The transmissivities of the Floridan aquifer are thought to vary by more than three orders of magnitude throughout the basin. Only a few measurements (pump tests) have been performed in the area. Analyzing the local fracture/matrix system at the site provided an evaluation of the Floridan aquifer transmissivity and storativity. More importantly, this test was intended to provide hydraulic characterization of the fracture/matrix system.

The field study was comprised of remote techniques as well as a site investigation. The remote technique is principally fracture trace analysis of aerial photographs. The site investigation includes ground truthing of the fractures and an aquifer test. The ground truth includes a VLF electromagnetic and DC resistivity tripotential survey across selected fracture traces in the vicinity of the pump test.

FRACTURE TRACE ANALYSIS AND GEOPHYSICS

The objective of the fracture trace analysis and geophysical surveys was to locate probable fracture zones for observation well locations. Fracture traces are linear features observable on aerial photographs which represent the surface manifestation of vertical zones of increased fracture density in the underlying bedrock. They can be recognized by linear patterns of soil zones, vegetation, stream segments, and solution features (in karst terraces). Several studies indicate that fracture traces are associated with zones of increased hydraulic conductivity (Stewart and Wood, 1986; Moore and Stewart, 1983; Parizek, 1976). A fracture-trace analysis of the region around ROMP 120 was completed using 1:80,000 black and white aerial photographs. Figure 1 shows the site with the fracture traces and test well locations.

Horizontal electrical profiles (HEP) were completed using the tri-potential method (Ogden, 1984; Habberjam, 1969). This DC resistivity method is sensitive to vertical, sheet-like features such as fracture zones. Three different electrode configurations are used to measure the apparent resistivity of the earth at each station. As described by Ogden (1984), conductive or resistive anomalies are revealed by particular variations in apparent resistivities calculated in each array. VLF resistivity profiles were attempted, but reception of the VLF signals was poor during the course of the survey, and accurate terrain resistivity values could not be obtained. Because the VLF method relies on distant VLF communications transmissions, local interference and ionosphere conditions can adversely affect signal reception.

AQUIFER TEST

A. Pre-Test Computer Simulation

The aquifer test will consist of pumping ROMP 120 and observing the drawdown at several observation wells. The pumping well is an 8-inch well cased through the surface material for approximately 100 feet and open hole to a depth of 400 feet. Observation wells will have 4 inch diameter casing for the first 100 feet. Shallow observation wells penetrate the first 50 feet of the Floridan aquifer; the deeper wells penetrate 200 feet.

Interpretation of aerial photos indicate that a significant fracture is situated about 100 or 200 feet southwest of ROMP 120. The fracture is aligned northwest-southeast, similar to the interpretations made on a regional scale by previous investigations. The two intermediate surface expressions are roughly perpendicular to

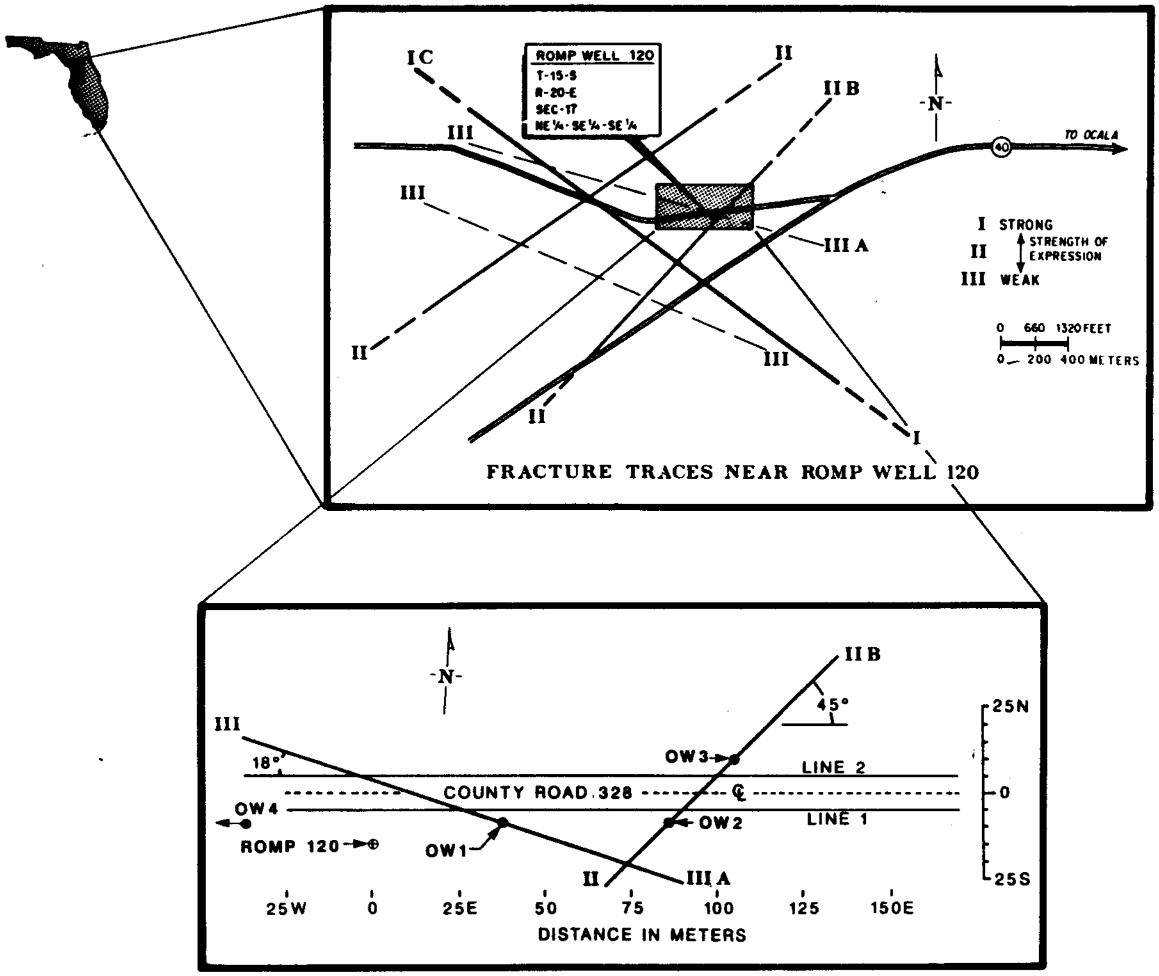

Figure 1. Location of fracture traces and monitoring wells in the study area.

this and are separated by about 2000 feet. The two weakest expressions complete the block.

Based on the assumption that the fracture traces represent zones of fracturing in the Floridan aquifer, a dual-porosity model was developed consisting of a single-layer (500 foot thick) representation of the Floridan aquifer. Primary and secondary traces were included as heterogeneities in the "fracture grid." This grid is composed of 960 blocks, covering an area of 19,272 by 19,000 feet, or about 13 square miles. Attached to each block is a one-dimensional "matrix grid" composed of 8 nodes. The hydraulic response of the entire area is controlled primarily by the transmissivity of the fracture grid and storativity of the matrix grid.

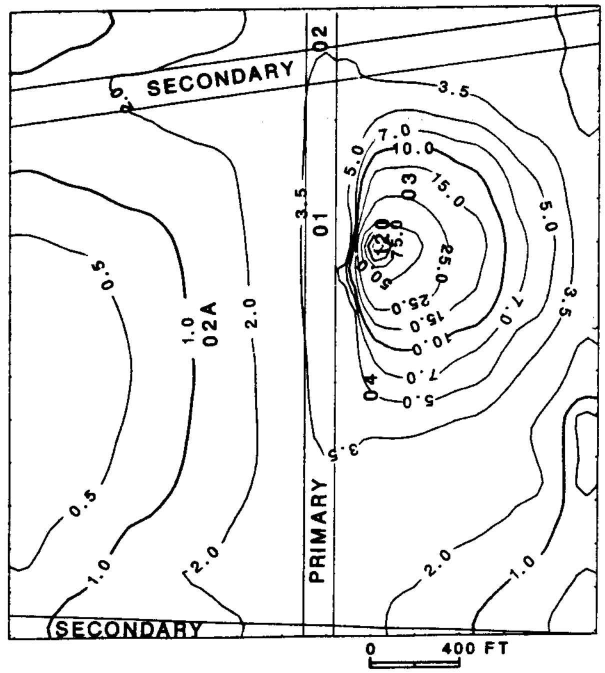

Figure 2. Pretest simulated drawdowns (psi) in the vicinity of ROMP 120 after 24 hours of pumping at 500 gpm.

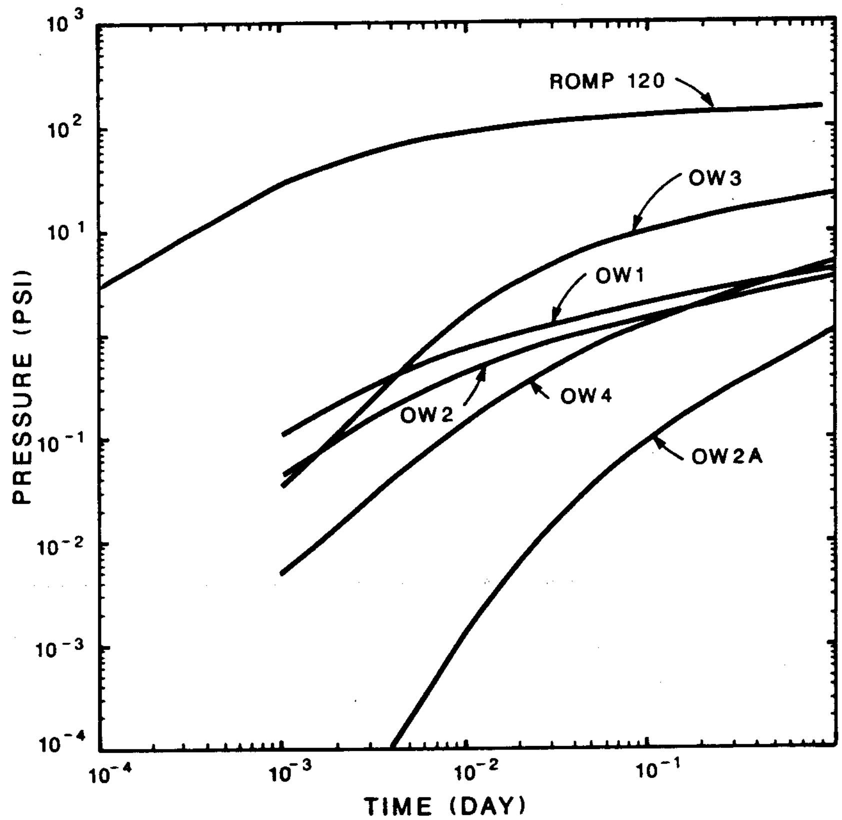

Figure 3. Pretest simulated drawdowns at potential observation wells.

The model was used to simulate a 24-hour pump test with a discharge of 500 gallons per minute (gpm). The drawdown, in pounds per square inch (psi), at the end of 24 hours is presented in Figure 2. Five possible locations for observation wells are shown. Wells 1 and 2 are situated within the primary fracture zone at distances of 300 and 1000 feet. Wells 3 and 4 are in the matrix block at distances of 300 and 700 feet. Well 2A (alternate) is 900 feet away on the opposite side of the primary fracture.

In Figure 3, predicted drawdowns for the aquifer test are given. The pressures vary from below detection to over 125 psi at the pumping well. For this conceptual model, the S-shaped curve, typical of dual-porosity systems, is not exhibited. The transition from the fracture to matrix probably occurs within the first minute of the test. This indicates that pressure transducers will be required to capture the early time behavior. Observation wells 1 and 2 behave differently from the others due to the difference in the fracture.

One psi corresponds to approximately 0.43 feet of drawdown. The simulated drawdowns were an overestimate of the actual drawdowns that were measured. While the simulations are probably not useful in deciding the measurement ranges of transducers that should be used, the results do indicate the relative change in response at the different proposed locations.

B. Hydrologic Testing: Procedures and Results

Hydrologic testing consisted of slug tests and a pumping test conducted to characterize the material properties of the site under investigation. The pump test was the primary source of information. The slug tests were performed to provide secondary information to supplement and correlate with the pump test data.

Prior to initiation of the aquifer test, slug tests were conducted in each of the four observation wells. The changes in head were achieved by means of a slug cylinder, which is a section of PVC pipe capped at both ends and weighted. The slug cylinder was used for both positive and negative displacement tests. The positive displacement corresponded to injecting the slug cylinder into the well, causing an increase in head. The negative displacement, or head decrease, was obtained by withdrawing the slug cylinder from the well.

The slug cylinder was constructed with a 5-foot section of 3½-inch o.d. threaded PVC pipe capped at both ends. To achieve the desired displacement, the cylinder was weighted with 1 gallon of distilled water, which combined with the weight of the cylinder resulted in an overall weight of approximately 15.3 lbs. The cylinder was designed to float; hence, the head change could be calculated from the known weight of the cylinder. In the 4-inch i.d. observation wells, the calculated head change was 2.82 feet.

The slug test data were recorded with an Enviro-Labs Model DL-120-MCP data logger. The logging sequence used was 60 readings at 1-second intervals. This sequence was appropriate because, in all cases, the displaced water level in the observation wells returned to its initial level in less than 60 seconds. The slug test results are presented in Figures 4a - 4d. Positive and negative results are depicted in the same plot.

Observation wells OW1, OW2 and OW3 (fracture-trace wells) all produced an oscillating or underdamped response to the sudden change in depth. This type of response is indicative of the high porosity associated with the fractures and results from inertial effects occurring in the large pore spaces of the fractured zone. Observation well OW4 demonstrated the overdamped response, which was expected since OW4 is a matrix block well.

The slug test provides a quick and economical means for quantifying the near well aquifer characteristics. A pump test, on the other hand, provides more of a regional characterization. This is because a pump test affects a much larger volume of material, hence local variability is obscured.

The pump test conducted at the study site commenced at 1400 hrs on February 2, 1988. The pumping rate was approximately 180 gpm (gallons per minute), as determined by an orifice method of measuring flow. All discharge water was piped away from the site through 1000 feet of 6-inch o.d. aluminum pipe. The water was discharged west of the site over the crest of a small hill. This was done to prevent the discharge water from artificially recharging the aquifer through surface infiltration. The duration of the pumping portion of the test was 24 hours. To monitor the progress of the test, periodic water-level measurements were taken with a hand-held QED water-level probe.

The pump test data was collected via two single-channel Terra 8D data recorders and the 8-channel Enviro-labs data logger. The logging sequence used for both drawdown and recovery is presented in Table 1. Observation wells OW3 and OW4 were each assigned a Terra 8D recorder. The Enviro-Labs recorder was used for observation wells OW1 and OW2. All observation well responses were measured using 5-psi transducers, allowing a maximum drawdown of approximately 11.5 feet. Observation well OW2 had an additional 25-psi transducer placed at a maximum submergence of 57.68 feet. inch an effort to quantify possible time delays of the pumping response associated with transducers placed at different depths. The Terra transducers accuracy was ±0.1% of full scale, which is equivalent to approximately ±0.01 feet. The Enviro-Labs transducers has an accuracy of ±0.5% of full scale, which, for a 5-psi transducer, was approximately 0.05 feet.

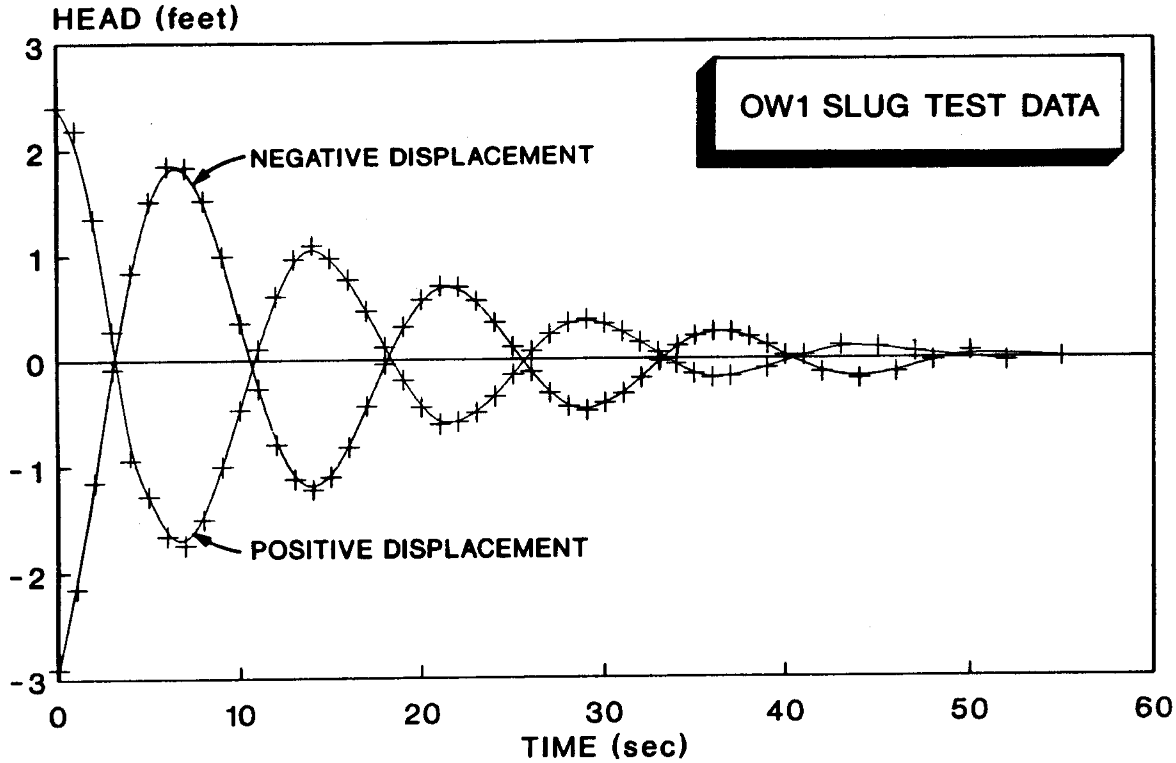

Figure 4a. Slug test response at well OW1.

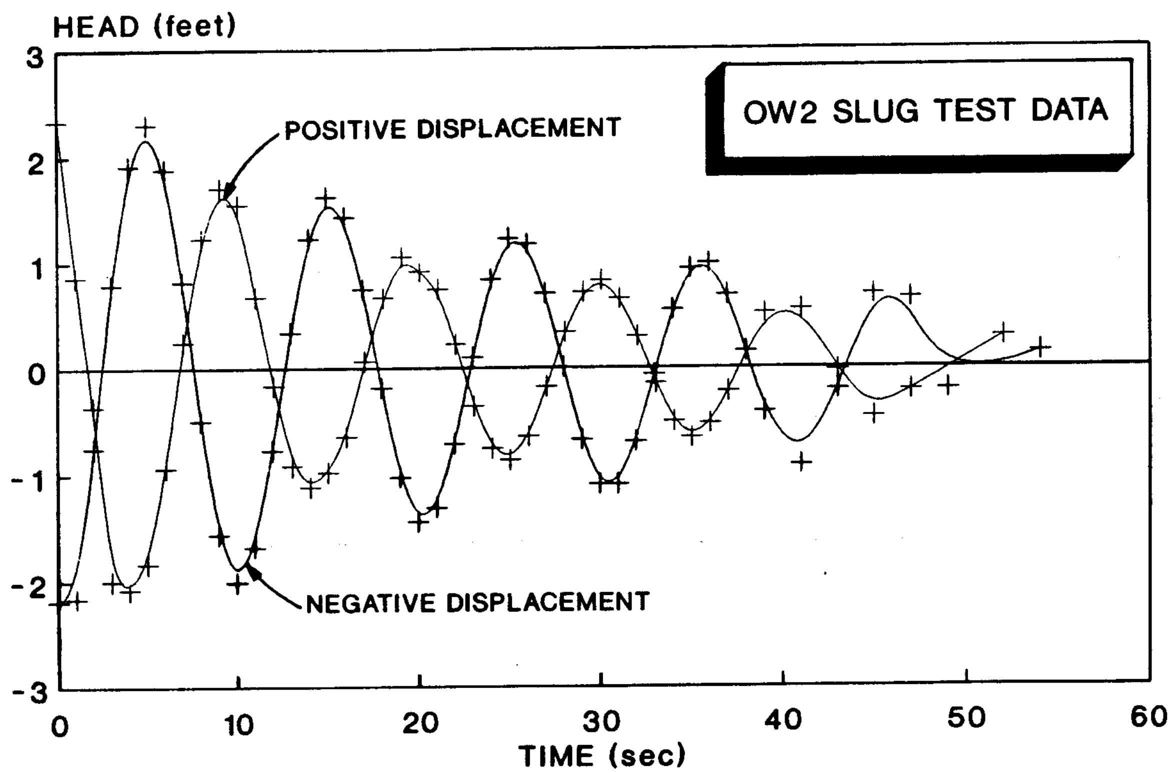

Figure 4b. Slug test response at well OW2.

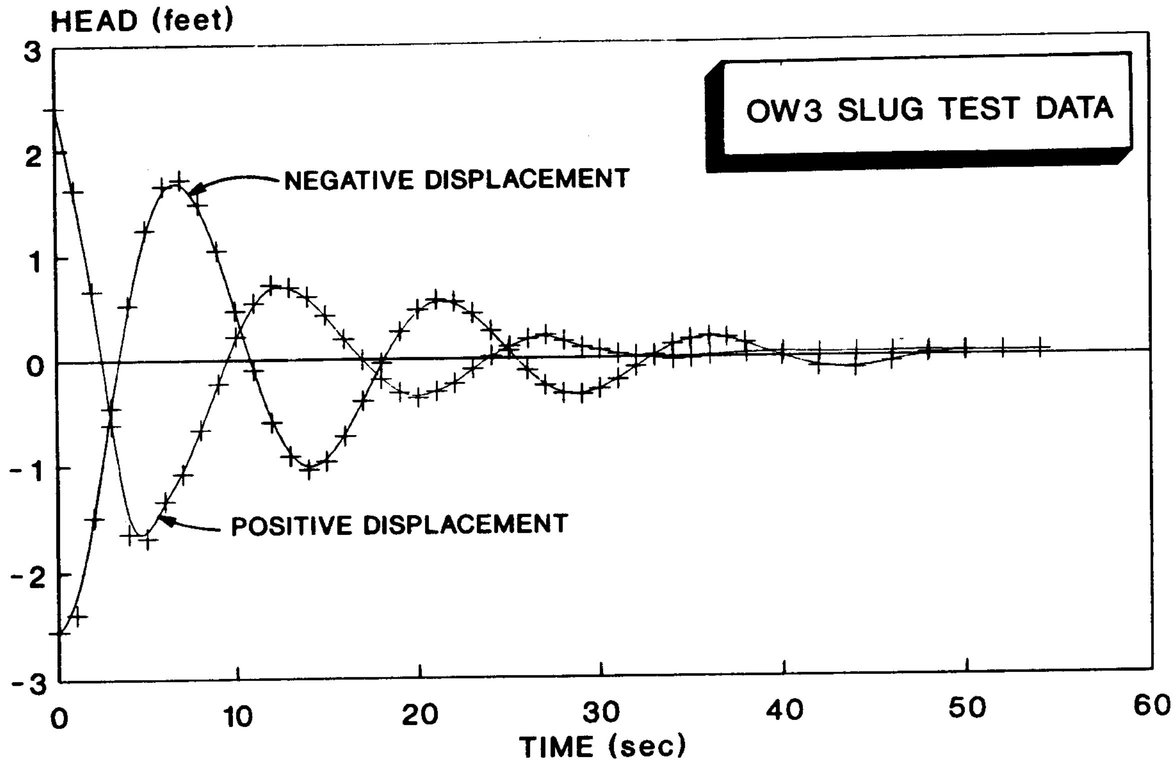

Figure 4c. Slug test response at well OW3.

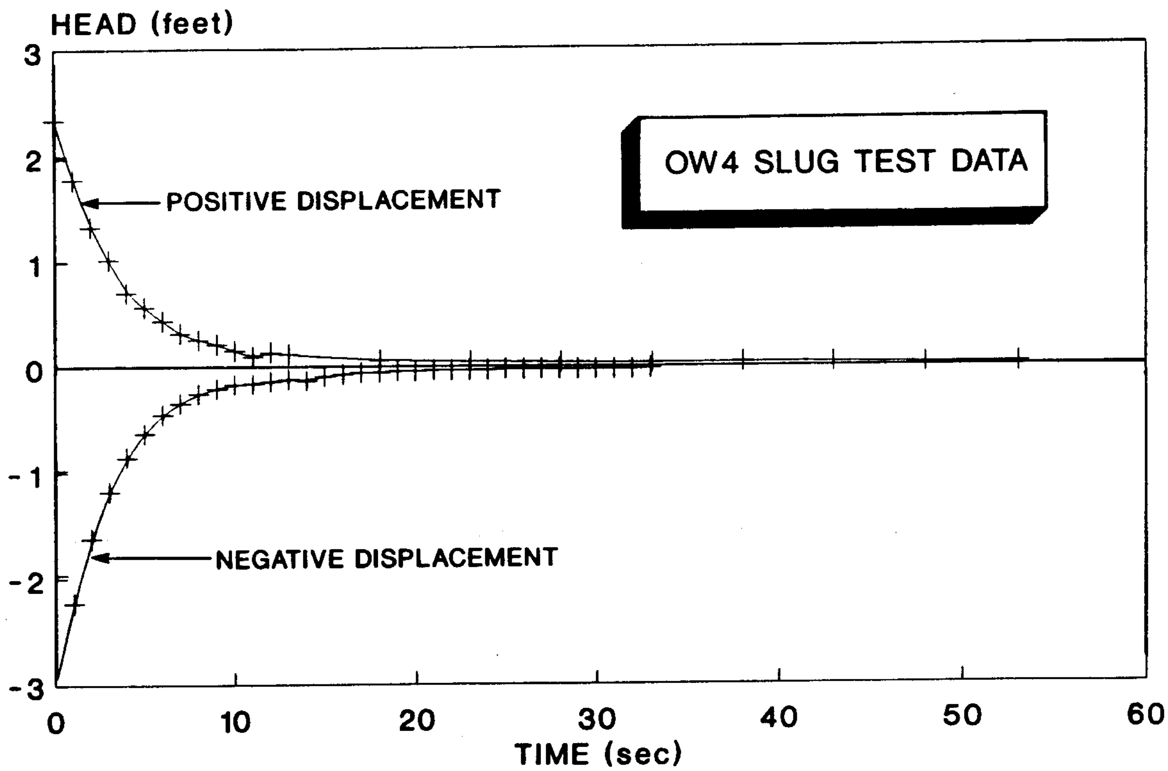

Figure 4d. Slug test response at well OW4.

Table 1. Logging sequence for both drawdown and recovery.

Number of Readings	Interval Between Readings (sec)	Cumulative Elapsed Time (sec)
150	1	150
105	10	1200
70	60	5400
36	300	16200
117	600	86400

Transducers were used to measure the water-level response data for the observation wells during the pump test. The early time oscillatory response of the water level in observation wells OW1 and OW3 was originally thought to result from either turbulence effects associated with turning the pump on or inertial effects of water passing through the highly permeable and heterogeneous Floridan aquifer. Because a similar oscillating behavior was observed during recovery (i.e., just after the pump was turned off), the effects were not believed to be caused solely by the pump. This type of response is commonly encountered in high permeability formations.

The pump was shut off after 24 hours to initiate the recovery portion of the pumping test. The maximum drawdown at the pumping well during withdrawal was 1.1 feet. The pumping well recovered to pre-pumping conditions in approximately 1 hour. Transducers were used to measure water-level recovery data for observation wells OW3 and OW4. Due to a transducer malfunction, recovery data was lost at wells OW1 and OW2. Observation wells had recovered to their initial pre-pumping water levels in less than 2 hours. Therefore, it was decided that there was no need to monitor the recovery for the proposed 24 hours.

The slug tests and pumping test constituted the hydraulic characterization phase of the investigation. Information gathered during these tests was used in assembling the fracture flow model. This information included aquifer properties determined from analysis of the hydrologic testing data. The results of these analyses are presented in the following section.

C. Analysis of Hydrologic Testing: Slug Test

The results of the hydrologic tests may be analyzed using appropriate techniques to determine estimates of transmissivity. The slug tests performed for this investigation showed an underdamped response in three of the four wells tested (OW1, OW2, OW3). This response produces an oscillation of the water level in the well due to inertial effects which are common in highly permeable aquifers. A method for analyzing this type of well response was developed by van der Kamp (1976). The van der Kamp solution assumes an underdamped response (i.e., water levels within the well oscillate about equilibrium with an exponentially decreasing amplitude with time). In general, the response can be described by:

$$w(t) = w_o \, e^{-\gamma t} \cos \omega t$$

where: $w(t)$ = water-level fluctuation,
ω = angular frequency of oscillation,
w_o = initial water level after release of slug,
t = time, and
γ = damping constant.

The parameters γ and ω can be determined using a least squares regression after an initial water-level oscillation amplitude, w_o, has been chosen. The above equation is a good approximation if the initial moments of displacement are disregarded.

Once γ and ω have been estimated, geometric well parameters can be used to calculate the aquifer transmissivity. The test conditions have been idealized by van der Kamp and are shown in Figure 5. The effective length of the water column is given by:

$$L = L_c + 3/8 \, L_f$$

where L_c is the length of the water column inside the casing and L_f is the length of the well filter. The dimensionless parameter d is calculated as follows:

$$d = \gamma/(g/L)^{1/2}$$

By equating inertial forces, the aquifer transmissivity can be calculated from:

$$T = b + a \, (\ln(T))$$

where:

$$a = r_c^2 \, (g/L)^{1/2}/8d$$

and

$$b = a[\ln \, (0.79 \, r_f^2 \, S(g/L)^{1/2})]$$

Here, r_c is the radius of the well casing, r_f is the radius of the filter, g is the acceleration of gravity, and S is the coefficient of elastic storage. Large variations in the values of r_f and S result in only small variations in the value of b, therefore, a good estimate of r_f and S is sufficient for most practical purposes (van der Kamp, 1976). The value of T is determined using an iterative process, by first presuming that T is roughly equivalent to b.

Some of the underlying assumptions of the van der Kamp solution are as follows:

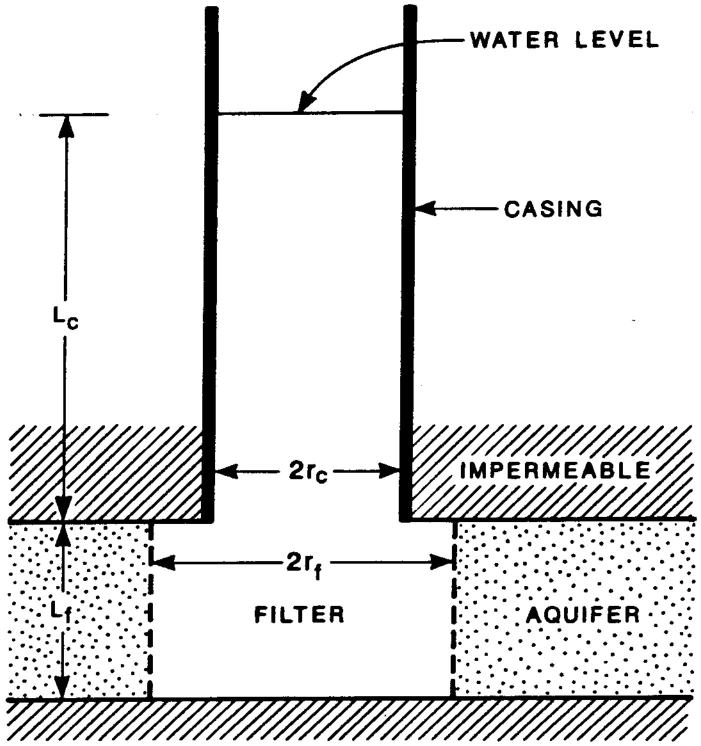

Figure 5. Diagram of idealized well-aquifer system (modified from van der Kamp, 1976).

- The well-aquifer system is underdamped, a condition easily observed by plotting water level vs. time.
- Water-level fluctuations are much smaller than the effective length of the water column.
- The hydraulic head in aquifer at infinite distance does not change with time.
- The water-level fluctuation at infinite time is zero.
- In the following equation, α must be less than 0.1:

  $$\alpha = 0.89\ (S/T)^{1/2}\ (\omega^2 + \gamma^2)^{1/4}\ r_f$$

- For laminar flow in the well casing, friction losses can be neglected for:

  $$4\nu/r_c^2 << \gamma$$

- For turbulent flow, losses will be negligible and the van der Kamp (1976) solution will apply if:

  $$0.005\ (w_o/r_c) << \gamma/w.$$

A summary of the estimated transmissivities is given in Table 2. Note that the difference in the two test results at each well is relatively small (i.e., less than 30 percent). These values represent aquifer properties in the immediate vicinity of the well. The results indicate that aquifer transmissivity in the vicinity of OW1 and OW3 is similar while at OW2 the aquifer is much more permeable (nearly an order of magnitude higher transmissivity). The high transmissivity observed at well OW2 was not expected, based on the clay infilling or mineralization observed during well development. It was originally thought that possibly OW2 was not sited on a fracture because the discharge waters during well development did not flow clear.

Table 2. Results of slug test analyses for observation wells.

Well	Displacement	Transmissivity ($feet^2/day$)	Hydraulic Conductivity (feet/day)
OW1	positive	6,585	16.5
OW1	negative	7,203	18.0
OW2	positive	27,635	69.1
OW2	negative	36,565	91.4
OW3	positive	3,982	10.0
OW3	negative	6,263	15.7
OW4	positive	2,158	5.4
OW4	negative	2,640	6.6

Hydraulic conductivities were obtained from the relationship:

$$K = T/b$$

where b (saturated thickness) is assumed to be 400 feet.

The well response during positive displacement of the slug test conducted at well OW4 is shown in Figure 4d. This well did not show the oscillatory response. This supports previous observations that the well was installed in a relatively less permeable material, probably a matrix block with few intersecting fractures. Therefore, the method used to analyze the data is the solution of Bredehoeft and Papadopulos (1980) given below:

$$\frac{H}{H_o} = F\left[\frac{r_s^2 S}{V_w C_w \rho_w g}, \frac{Tt}{V_w C_w \rho_w g}\right]$$

where: H/H_o = dimensionless head change in well,

r_s = radius of well in test interval,

S = storage coefficient,

T = transmissivity,

t = time after pressurization,

V_w = volume of water within pressurized section,

C_w = compressibility of water,

ρ_w = density of water, and

g = gravitational acceleration.

The slug test results show significant variability in aquifer parameters at a local scale. This is due to the heterogeneous nature of the aquifer. These results were limited by the scale of the test and were therefore thought to be unusable as a representation of the transmissibility of the aquifer at a regional scale. This information can normally be better obtained from the pumping test results which consider a larger distribution of aquifer characteristics.

D. Analysis of Hydrologic Testing: Pump Test

The results of the pumping test performed for this study were analyzed by two methods; the Theis method for unsteady-state flow in a confined aquifer, and Jacob's method. These were the two simplest means of representing the test conditions. As presented in this section, the response curve does not require more elaborate techniques such as unconfined conditions, delayed-yield, or double porosity.

The Theis equation describes the drawdown, s, in a pumping well or observation well as a function of the aquifer transmissivity, T, the aquifer storage coefficient, S, and well discharge, Q, as shown below.

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-u}}{u} du$$

where:

$$u = \frac{r^2 S}{4Tt}$$

r = distance to observation well, and
t = time since pumping began.

Using the method of images, Theis (1935) also proved that the recovery of a well can be described by

$$s' = \frac{2.30\ Q}{4\pi T} \log \frac{t}{t'}$$

where: s' = residual drawdown, i.e., the difference between the original water level prior to pumping and the water level measured at a time t' after pumping has stopped,

t' = time since pumping stopped, and

t = time since pumping began.

The primary assumptions included in the Theis (1935) derivation are given below.

- The well discharges at a constant rate.
- The well is of infinitesimal diameter and fully penetrates the aquifer.
- The initial drawdown in the aquifer (prior to pumping) is zero.
- Drawdown approaches zero as distance from the well approaches infinity.
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the aquifer tests.
- Storage in the well can be neglected.

Residual drawdowns are plotted as a function of dimensionless time, t/t', on semilog paper. The change in residual drawdown over one log cycle, $\Delta s'$, is used to calculate transmissivity from the equation below.

$$T = \frac{2.3\ Q}{4\pi \Delta s'}$$

Jacob's method (Cooper and Jacob, 1946) is based on the Theis formula but conditions are more restrictive in that distance to the pumping well (r) should be small and the time (t) should be large.

The data from wells OW1 and OW3, used in the aquifer test analysis, and the parameters used in the application of each analytical method are given in Figures 6 through 7. A summary of the transmissivity and storage coefficients estimated from these analyses is given in Table 3. As noted in the table, data from OW2 could not be

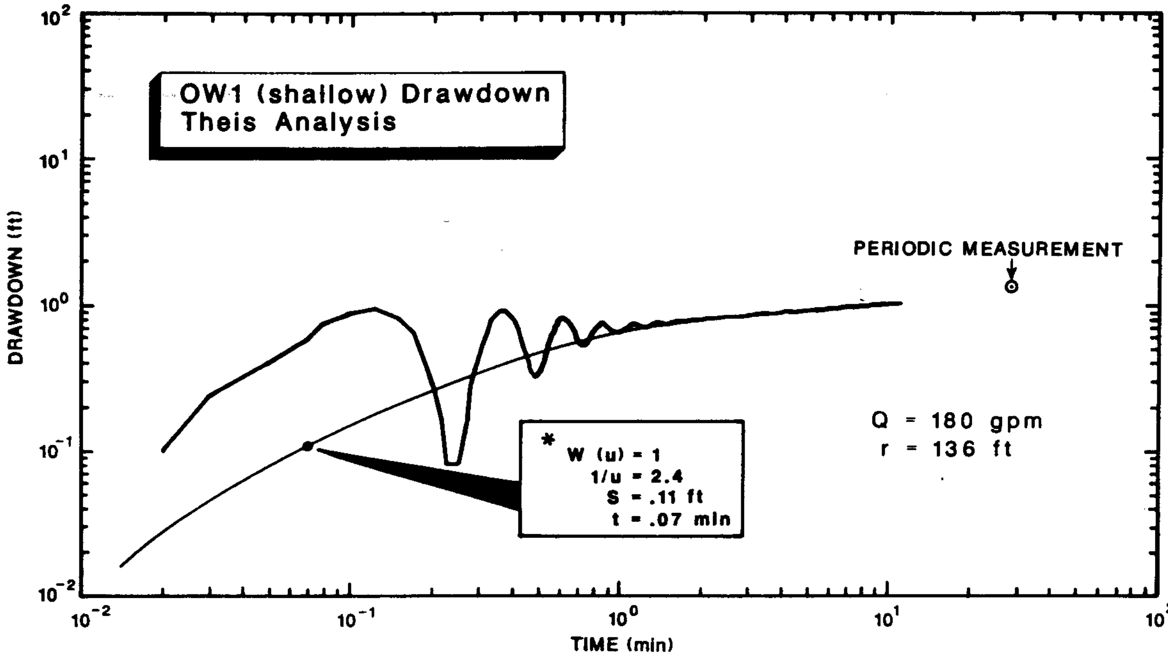

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Figure 6a. Pump test interpretation using the deep transducer at observation well OW1 (shallow) using Theis method.

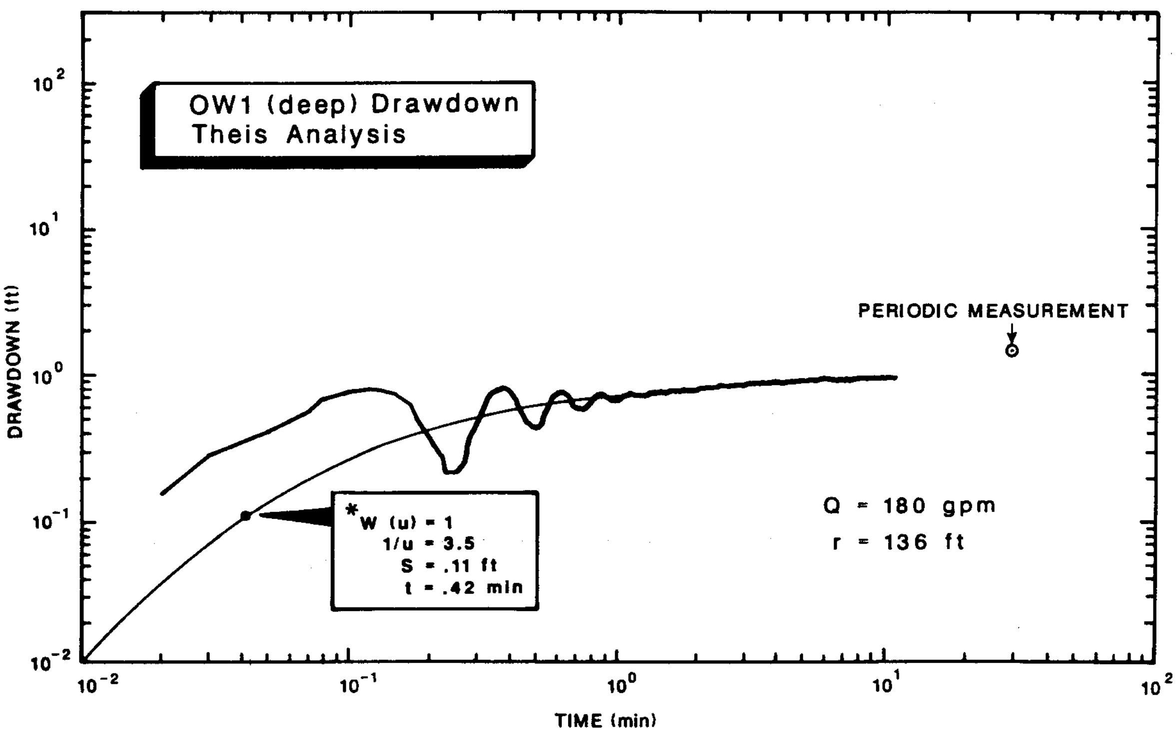

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Figure 6b. Pump test interpretation using the deep transducer at observation well OW1 (deep) using Theis method.

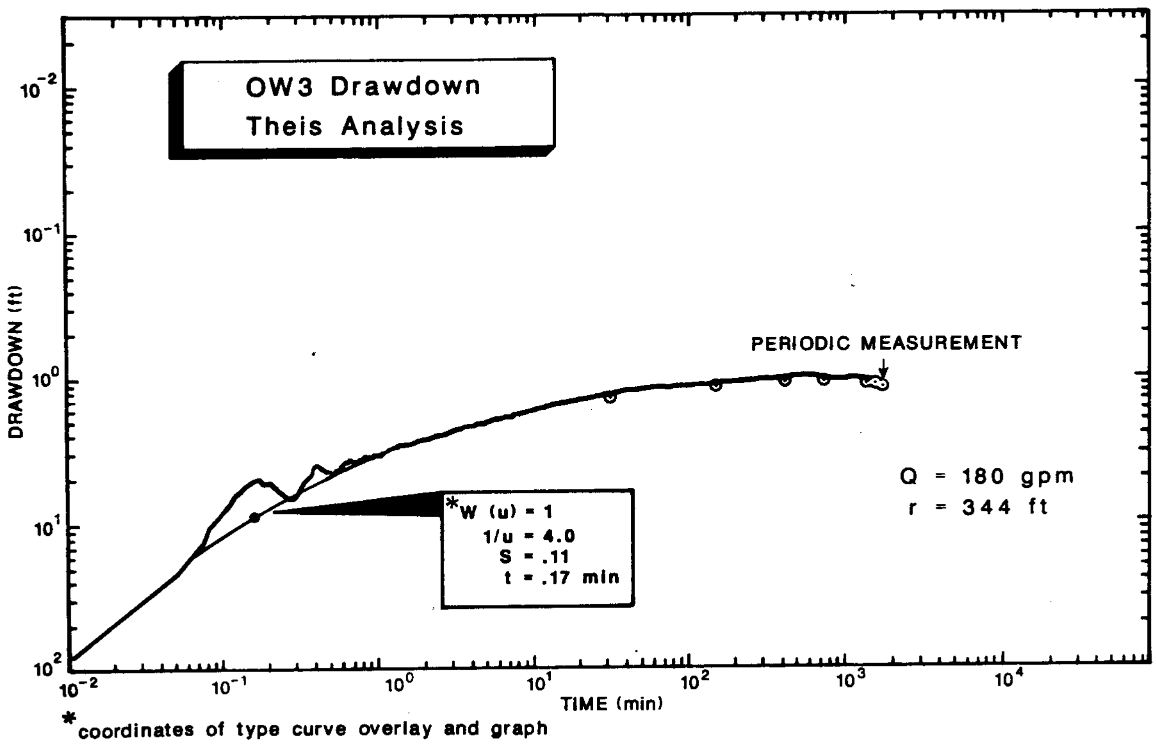

Figure 6c. Pump test interpretation at observation well OW3 using Theis method.

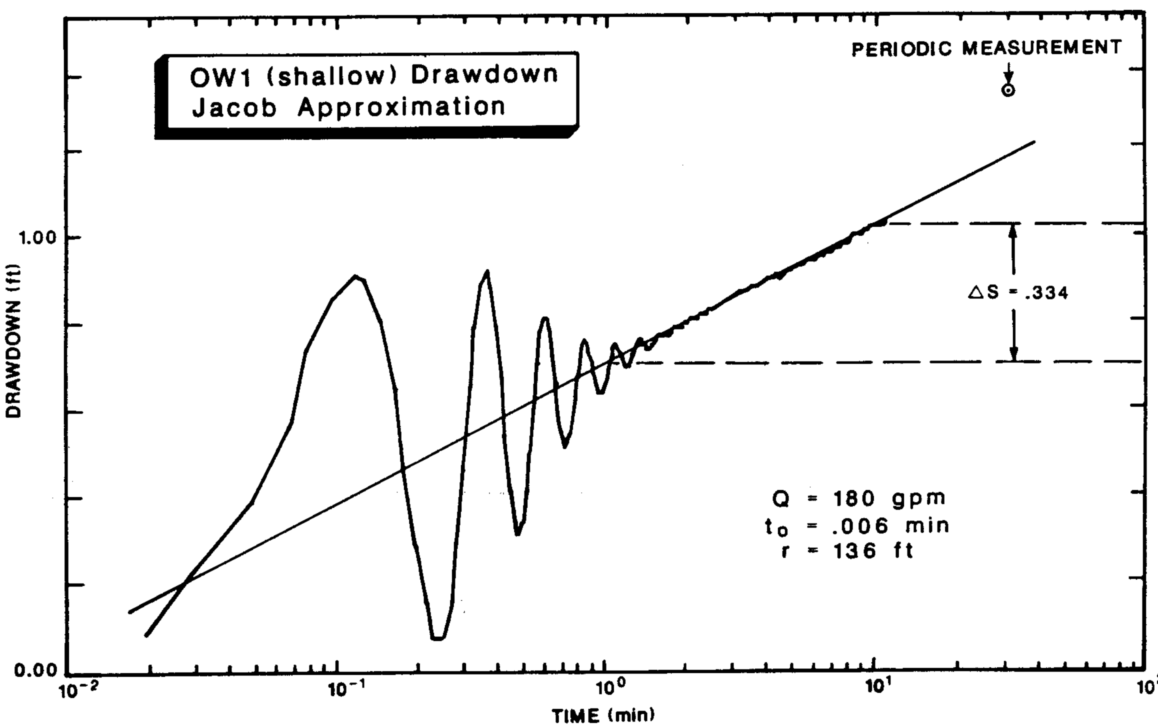

Figure 7a. Pump test interpretation using the shallow transducer at observation well OW1 (shallow) using Jacob approximation.

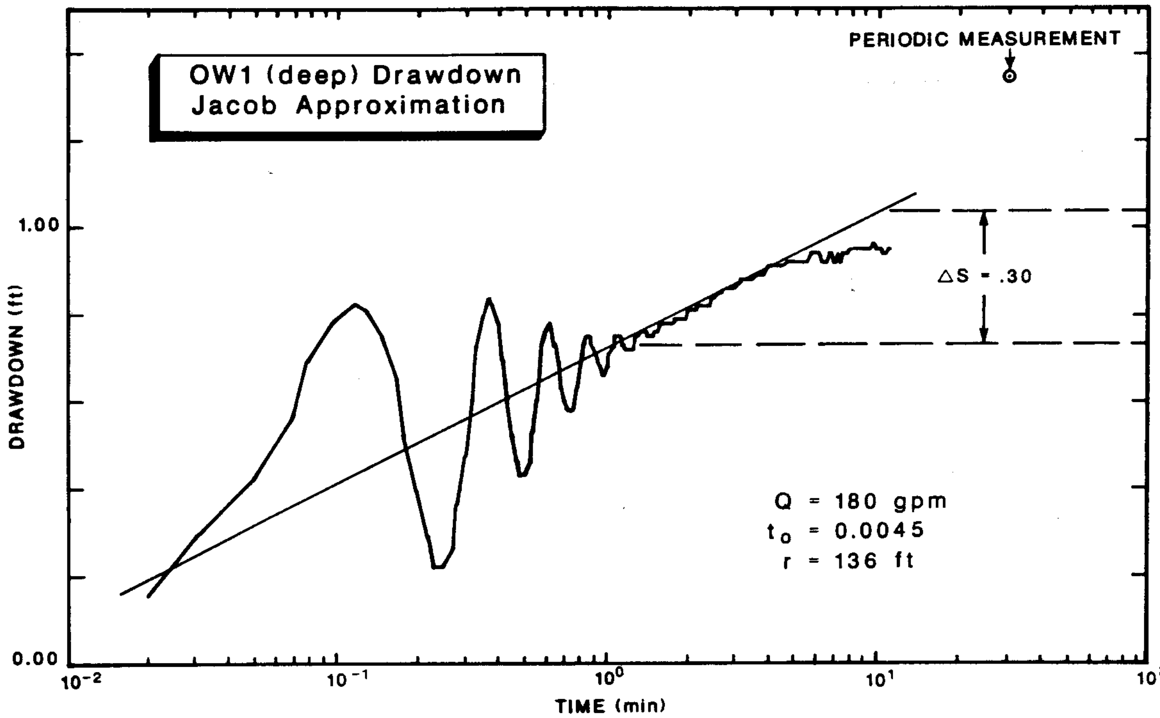

Figure 7b. Pump test interpretation using the deep transducer at observation well OW1 (deep) using Jacob approximation.

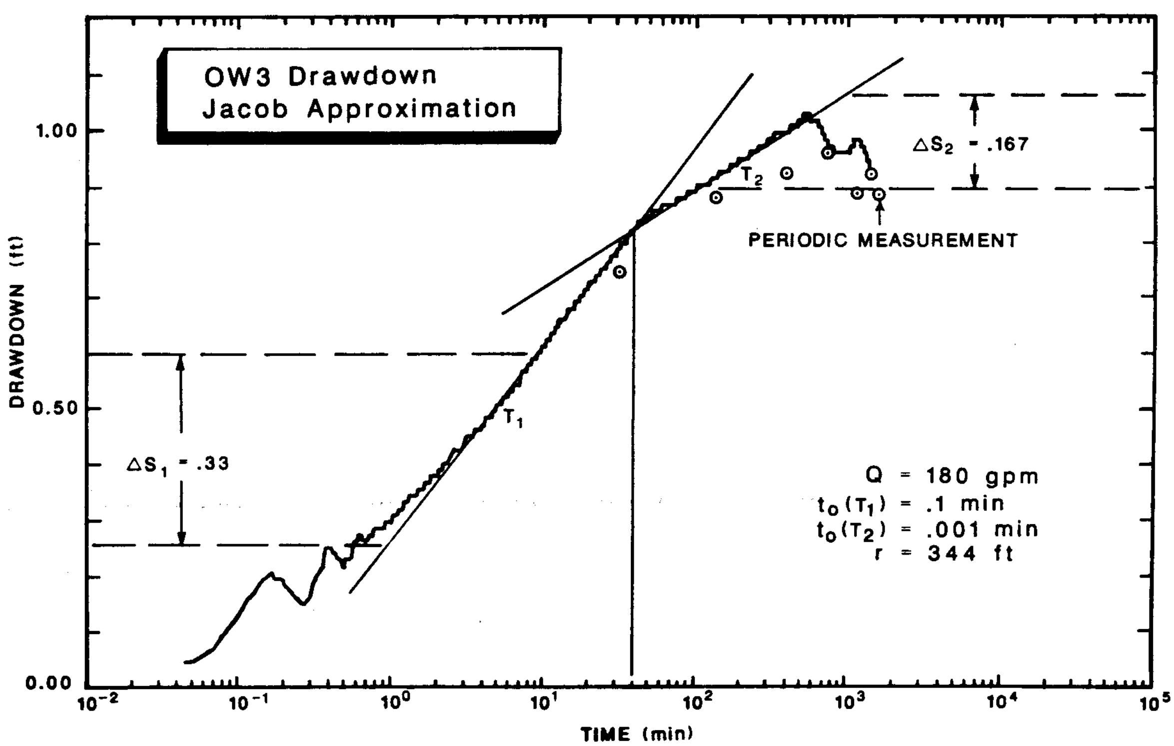

Figure 7c. Pump test interpretation at observation well OW3 using Jacob approximation.

analyzed because a measurable response was not observed. This type of response demonstrates that OW2, while being highly transmissive at a local scale, has minimal hydraulic connection to the other well sites. It appears that OW2 intersects an infilled fracture zone, isolating it from the surrounding area. As discussed in the previous section, a malfunctioning transducer resulted in the loss of recovery data from OW1. Therefore, a recovery analysis could not be performed at this well.

Table 3. Results of aquifer test analyses.

	Transmissivity ($feet^2/d$)		Storage Coefficient	
Well	Jacob	Theis	Jacob	Theis
OW1 (shallow) drawdown	19,021	25,070	$9.6x10^{-6}$	$1.11x10^{-4}$
OW1 (deep) drawdown	21,176	25,070	$8.03x10^{-6}$	$4.59x10^{-5}$
OW3 drawdown*	19,021 (T_1)	25,070	$2.50x10^{-5}$ (S_1)	$2.50x10^{-5}$
	38,041 (T_2)		$2.50x10^{-7}$ (S_2)	
OW3 recovery	21,907	22,981	$2.31x10^{-5}$	$2.95x10^{-5}$

*For OW3 analysis using the Jacob method T_1 represents early time and T_2 represents late time.

NOTE: No values from OW2 and OW4 because no measurable response was observed.
No recovery analysis at OW1 due to loss of data from transducer.
No recovery analysis at OW1 due to loss of data from transducer.

The data from OW4 were not analyzed due to the occurrence of the Noordbergum (Rodriques, 1983) effect which demonstrates that the well response violates the assumptions of analytical methods used here. The Noordbergum effect is a reverse water-level response observed in aquitards or aquifers separated from the pumped aquifer by aquitards. This type of response reflects the difference in aquifer properties in the matrix block from those in the fractured media.

The results of the pumping test analysis provide estimates of transmissivity ranging from $1.9x10^4$ - $2.5x10^4$ $feet^2/d$. A higher estimate of $3.8x10^4$ $feet^2/d$ was obtained from late time drawdown data at OW3, however, this may result from the cone of depression intersecting another fracture as the pressure response emanates from the pumped well. This explanation is unlikely because a similar response should have been measured at OW1. Storage estimates vary over an order of magnitude ranging from 8.0×10^{-6} - 1.1×10^{-4} (analysis of late time data from OW3 excluded). The results provide reasonable estimates of the local aquifer transmissivity in the northern region of the county, based on knowledge of lithology, structure, and geophysical responses gained during this study. These values of transmissivity more likely represent the fractured media, while estimates of matrix properties are better represented by slug test results at OW4.

E. Early Time Oscillatory Analysis

Further experimenting with the early time data from those wells displaying underdamped responses to the pump test enabled discovery of a reasonable way to analyze the early time data. By applying a filter composed of the Theis equation that fits the later slope of the data it was possible to segregate a data set that could be used with a van der Kamp fit. The filtering serves to isolate the variables and basically separate the data by superposition. Both these operations are performed using the same equations and assumptions as presented in the earlier analyses.

Figures 8a and 8b show the van der Kamp reaction of the filtered data and Table 4 shows the final results for the transmissivities obtained using this method. OW1 (deep) was almost exactly the same as OW1 (shallow).

Table 4. Results of van der Kamp analysis of Theis deviation.

Well	Transmissivity (feet^2/d)
OW1 (shallow) drawdown	19,579
OW3 drawdown	19,113

The transmissivity values in Table 3 are very close to the pump test interpretation using the Jacob method.

DISCUSSION

From the Figures 6a, 6b, and 6c showing the Theis interpretations of the pump test data it can be seen that the first 2 hours of data would have been sufficient to perform the analysis. Limiting the pump test to a two-hour interval would reduce costs by limiting manpower and equipment. Extensive discharge pipe would not be needed to avoid artificial recharge.

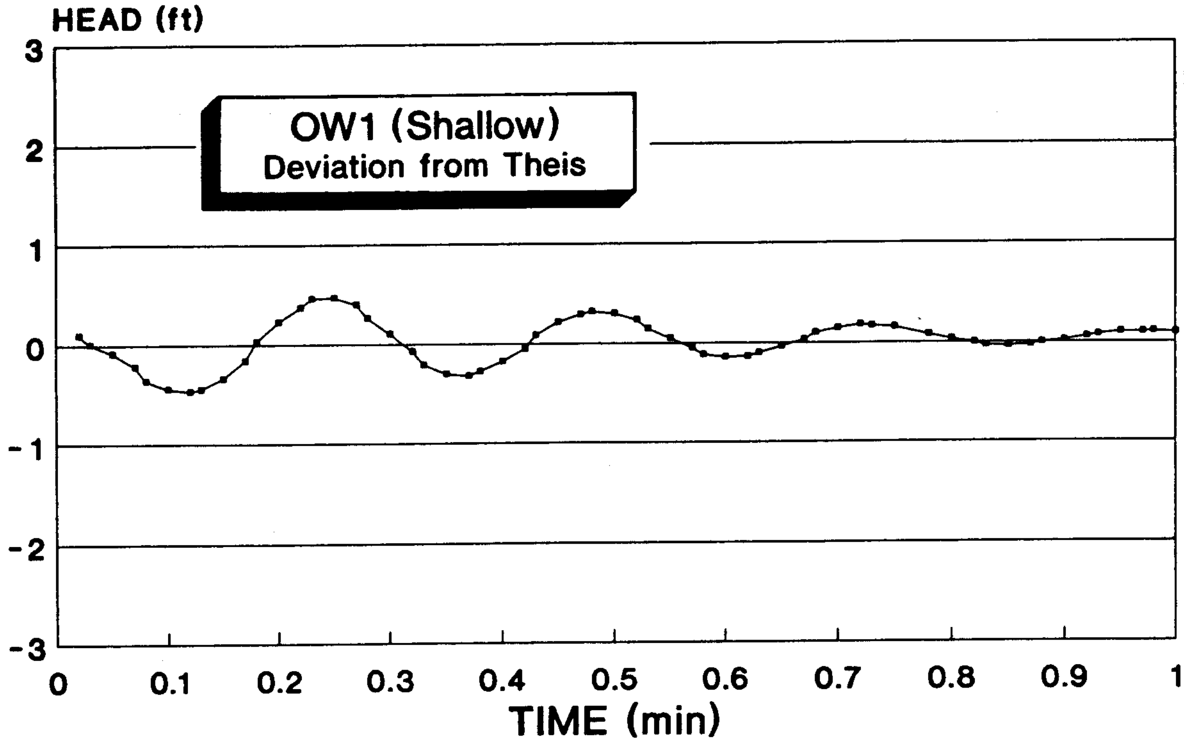

Figure 8a. Residual oscillatory responses at observation well OW1 (shallow) after applying Theis filter.

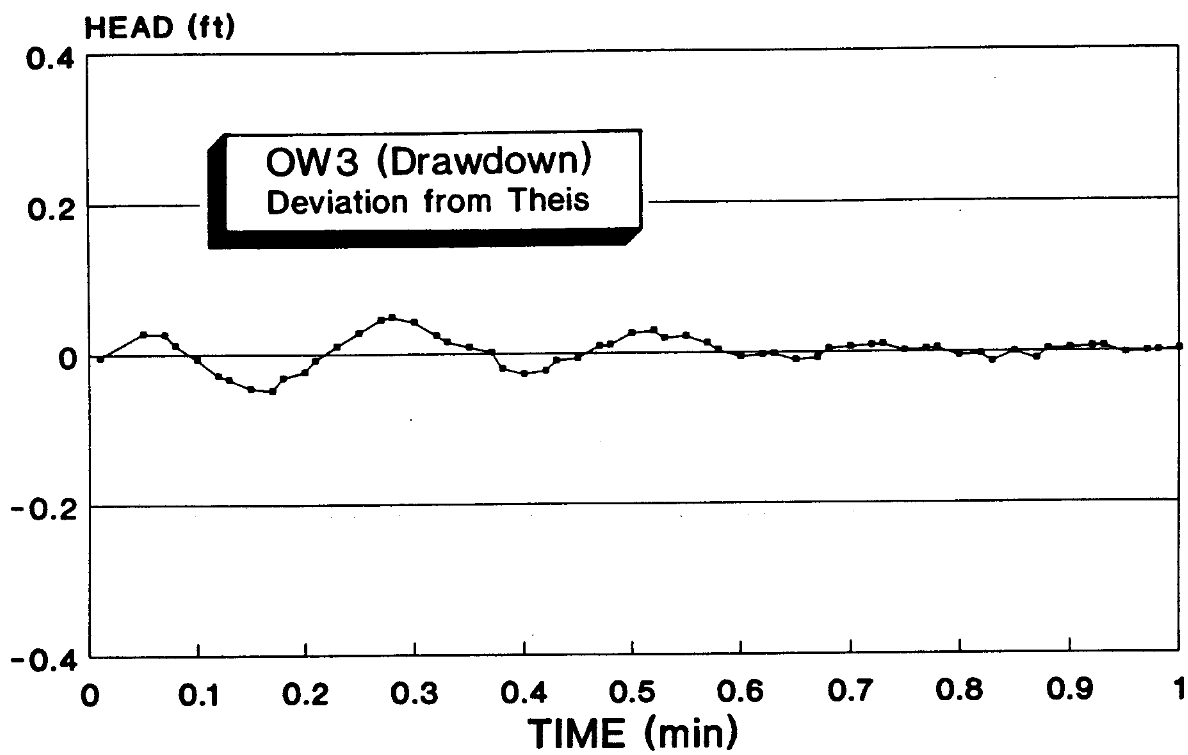

Figure 8b. Residual oscillatory responses at observation well OW3 after applying Theis filter.

There are two disadvantages to the early time method. For example leakance is difficult, if not impossible, to determine and boundary effects probably are not observable without longer-term data.

Because the site was included in the regional dual-porosity model, a composite diagram of the well test and model response can be developed. In Figure 9, a conceptual representation of the monitor well response is shown in relation to the two Theis curves that envelope the combined system response. Throughout the course of the pump test, the heads in the observation wells follow the local fracture curve. This is separated from the regional matrix curve by approximately a four orders of magnitude shift in time, based on the difference in storativities. It would have been very costly to continue the test for several weeks or more in order to verify where the well response merged with the limiting matrix curve.

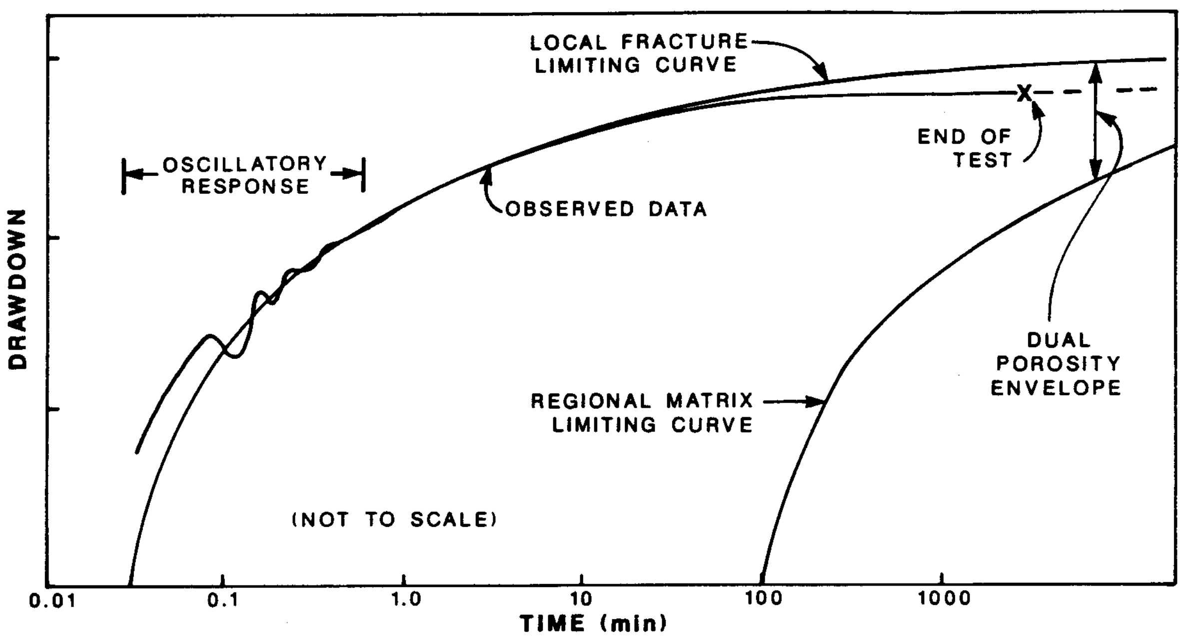

Figure 9. Conceptual composite of aquifer test and dual-porosity model response.

ACKNOWLEDGEMENTS

The authors wish to thank Paul Sims for support in conducting the field testing and preliminary interpretation, and Dr. Allen M. Shapiro for sharing his thoughts and experience with similar phenomena in Illinois.

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Daniel A. Giffin is a Senior Geologist specializing in implementing field programs for GeoTrans, Inc. He received his B.S. degree in Geology from West Virginia University in 1984. He is currently involved in a contract for Florida Power & Light at their Pepper Steel and Alloy site, a Superfund site classified by the EPA as requiring compliance with Level C EPA-stipulated safety criteria. He has also acted as field manager at sites near Niagara Falls, New York, including Love Canal, Hyde Park, S-Area, and 102nd Street landfills. He has assisted in the characterization and computer modeling of hydrogeologic systems and organization and evaluation of hydrogeologic data, and has experience in conducting geophysical investigations. (GeoTrans, Inc., 250 Exchange Place, Suite A, Herndon, Virginia 22070, (703) 435-4400)

David S. Ward is a Principal Engineer at GeoTrans, Inc. He received his B.S.C.E. from Lehigh University and M.S. degree in Civil Engineering from Princeton University in 1977. His expertise is development, documentation, application, and quality assurance associated with computer models for flow, heat, and contaminant transport in the saturated and unsaturated zones. Mr. Ward has managed several projects concerned with performance assessment modeling of high-level nuclear waste repositories. He has performed benchmarking, verification, validation, and application of groundwater models to several nuclear waste sites, hazardous waste sites, and water resource problems. (GeoTrans, Inc., 250 Exchange Place, Suite A, Herndon, Virginia 22070, (703) 435-4400)

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