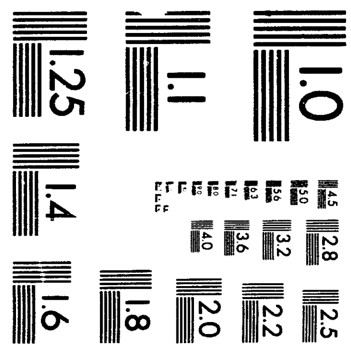
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5.6
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1 of 1

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APPLICABILITY OF SLUG INTERFERENCE TESTING OF HYDRAULIC CHARACTERIZATION OF CONTAMINATED AQUIFER SITES

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APPLICABILITY OF SLUG INTERFERENCE TESTING FOR HYDRAULIC CHARACTERIZATION OF CONTAMINATED AQUIFER SITES

by

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Aquifer test methods available for characterizing hazardous waste sites are sometimes restricted because of problems with disposal of contaminated groundwater. These problems, in part, have made slug tests a more desirable method of determining hydraulic properties at such sites. However, in higher permeability formations (i.e., transmissivities $\geq 1 \times 10^{-3}$ m^2/s), slug test results often cannot be analyzed and give, at best, only a lower limit for transmissivity. A need clearly exists to develop test methods that can be used to characterize higher permeability aquifers without removing large amounts of contaminated groundwater.

One hydrologic test method that appears to hold promise for characterizing such sites is the slug interference test. To assess the applicability of this test method for use in shallow alluvial aquifer systems, slug interference tests have been conducted, along with more traditional aquifer testing methods, at several Hanford multiple-well sites. Transmissivity values estimated from the slug interference tests were comparable (within a factor of 2 to 3) to values calculated using traditional testing methods, and made it possible to calculate the storativity or specific yield for the intervening test formation. The corroboration of test results indicates that slug interference testing is a viable hydraulic characterization method in transmissive alluvial aquifers, and may represent one of the few test methods that can be used in sensitive areas where groundwater is contaminated.

INTRODUCTION

Pacific Northwest Laboratory[a], in cooperation with Westinghouse Hanford Company, is providing hydrologic testing support for hydraulic characterization investigations at various RCRA and CERCLA operable unit facilities on the Hanford Site. Current hydrologic characterization studies at Hanford have, in some cases, been restricted by existing site conditions, such as contaminated groundwater, purge-water disposal problems, high formation permeabilities, etc. The presence of contaminated groundwater and, in some locations, areas of extremely high transmissivity greatly diminishes

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the use of standard hydraulic test methods to hydrologically characterize subsurface materials. A need clearly exists for developing new test methods and/or modifying currently used techniques to improve ongoing and future hydraulic characterization investigations. Of particular interest are test methods that can be performed rapidly, and that minimize the removal of large quantities of water (i.e., tests that minimize purge-water disposal problems).

One test method that appears to hold particular promise is slug interference testing. This test requires a two-well installation: a stress well and an observation well. The general test procedure requires initiating an instantaneous head increase or decrease at the stress well, and monitoring the associated formation response at the neighboring observation well. Analysis of the monitored pressure response at the observation well provides estimates of the formation transmissivity and storativity.

Use of slug interference testing has been infrequent in the past, with its function primarily limited to hydraulically characterizing confined aquifers and/or fractured rock formations having low storativities (between 10^{-4} and 10^{-6}) [e.g., Novakowski (1)]. The objective of this study is to illustrate the applicability of slug interference testing for hydraulically characterizing shallow alluvial formations under unconfined or semiconfined conditions (i.e., storativity between 10^{-4} and 10^{-1}). Results from a field-test example are also included.

TEST THEORY

The analytical solution for a slug test response for a stress well with a finite radius within an aquifer containing a semicompressible fluid was first presented in Cooper et al. (2). In their article, type curves were presented that related dimensionless head response, H_D, versus the dimensionless time parameter, β, for various values of the dimensionless storage parameter, α, at the stress-well location where

$$H_D = H/H_o \qquad \text{(Eq. 1)}$$

$$\beta = Tt/r_c^2 \qquad \text{(Eq. 2)}$$

$$\alpha = r_w^2 S/r_c^2 \qquad \text{(Eq. 3)}$$

where

H = observed head at time t, minus pretest static head level in well

H_o = instantaneous head change applied to well

T = transmissivity of test interval

t = test time

r_c = radius of well casing in the interval over which head change takes place

r_w = effective radius of well within test interval

S = storativity of test interval.

The type curves can be used to match the slug test response data at the stress well to solve for transmissivity and storativity using equations (2) and (3), respectively. The Cooper et al. (2) analytical solution in theory is strictly valid only for a fully penetrating well in a confined aquifer. Their solution, however, yields acceptable results for partially penetrating wells and unconfined aquifer tests provided that the saturated thickness of the unconfined aquifer does not change significantly [Walter and Thompson (3)] and radial flow conditions (no significant vertical flow components) exist. Although these conditions may be violated to some degree at the stress well, they should be acceptable at nearby points of observation.

Novakowski (4) presented a program (TYPCURV) that can generate slug interference test type curves based on the analytical solutions and boundary conditions presented in Cooper et al. (2). The program was used for developing predictive test responses and the test-example analysis presented in this paper. As indicated previously in Spane (5) and Spane and Thorne (6), slug interference tests are expected to provide valid characterization information for test intervals that exhibit confined and semiconfined conditions, and for unconfined aquifers that display test responses reflective of time-drawdown behavior that is not significantly influenced by delayed-yield (gravity flow/vertical flow components) effects. The presence of delayed-yield behavior can be discerned by converting the recorded slug test data to an equivalent head response that would be observed for a constant-rate pumping test. Conversion of slug test response data to equivalent head values associated with constant-rate pumping tests can be accomplished following the transformation procedure described in Peres et al. (7). The presence of delayed-yield behavior then can be assessed using pressure derivative analysis of the equivalent head response. Spane (5, 8) presents a more detailed description of the conversion procedure and use of pressure derivative diagnostic methods.

FACTORS AFFECTING SLUG INTERFERENCE RESPONSE

Factors influencing the transmission and amplitude of the slug interference response include the transmissivity, storativity, and anisotropy of the aquifer; radial distance; and partial penetration and wellbore storage characteristics of the stress and observation well. The influence of these individual factors is examined in the following discussion; more detailed discussions are presented in Novakowski (1, 4) and Spane (5).

Transmissivity

Although analyzable slug test responses at the stress well are limited to test formations with transmissivities of 10^{-3} m^2/s or less [Spane (5)], Fig. 1 indicates that slug interference responses for transmissivities of 10^{-3} m^2/s or more are readily discernible 3 m from the stress-well location (Note: A wellbore radius of 10 cm was assumed). As indicated in the figure, for a given observation point location, transmissivity has no affect on the magnitude of test response, but does exert a strong influence on the predicted slug interference response time, causing the interference response to shift horizontally on the plot. High aquifer transmissivities are associated with fast test responses, while lower transmissivities are associated with lagged (delayed) interference responses.

[Place Fig. 1 Here]

Storativity

Fig. 2 shows the predicted slug interference response for the same test-site conditions for an aquifer transmissivity of 10^{-3} m^2/s and storativity range of 10^{-4} to 10^{-1}. As shown, the shape (amplitude) of the slug interference response at the observation well is strongly influenced by the storativity of the aquifer. For this reason, slug interference testing is far superior to single-well slug tests for the characterization of this hydraulic parameter.

[Place Fig. 2 Here]

Radial Distance

Fig. 3 shows the predicted maximum slug interference test response as a function of radial distance from the stress-well location for a storativity range 10^{-4} to 10^{-1}, and a wellbore radius of 10 cm. As expected, the ability to detect a response is enhanced the closer the observation well is located to the stress well and the lower the storativity value of the geologic material. For the storativity range considered to be representative of most shallow alluvial aquifer conditions (elastic storage component of 10^{-2} to 10^{-4}), slug interference responses should be observable to maximum distances between 8 and 30 m from the stress well.

[Place Fig. 3 Here]

Observation Wellbore Storage

Significant observation wellbore storage tends to cause the well response to be lagged and attenuated from the predicted response, which, in the previous discussion, assumes that observation wellbore storage is negligible compared to that of the stress well. Novakowski (1) presents a graphical method for analyzing slug interference responses for cases in which wellbore storage at the observation well is or is not significant.

Partial Penetration

The previous discussion also assumes that the stress and observation wells completely penetrate a homogeneous and isotropic aquifer. The analysis method presented in Novakowski (4) and Spane (5), therefore, cannot be rigorously used to analyze test results having conditions of partial well penetration or vertical anisotropy (i.e., unequal vertical and horizontal hydraulic conductivity).

The effects of partial penetration cause distortion of the radial equipotential pattern that would normally develop during testing within a homogeneous, isotropic aquifer surrounding a fully penetrating stress well. Partial penetration effects cause additional drawdown to occur within the section of the aquifer intersected by the stress well-screen depth interval, and less drawdown to occur within the nonscreened aquifer section. This results in vertical flow components. Deviations induced by partial penetration are more significant near the stress well and diminish with distance. As indicated by Hantush (9), the flow pattern during hydrologic testing is essentially radial for observation well distances $\geq$ 1.5 times the aquifer thickness; for practical purposes, equations based on fully penetrating stress wells (e.g., Theis equation) provide sufficiently accurate results for observation well distances (r) as small as the aquifer thickness (b), provided that $u < 0.1\ (r/b)^2$ where $u = r^2\ S/4\ T\ t$.

Vertical Anisotropy

The effects of vertical anisotropy ($K_v \neq K_h$ where K_v = vertical hydraulic conductivity, and K_h = horizontal hydraulic conductivity) also tend to accentuate test response deviations caused by partial penetration. Because of the stratification evident to some degree in most sediments, vertical anisotropy would be expected to influence test results obtained within sedimentary alluvial aquifers. Within unconfined aquifers, where the vertical anisotropy ratio is less than 1 ($K_v/K_h < 1$), the effects of elastic storage and delayed yield are accentuated during the aquifer test response [Neuman (10)].

Hantush (11) reports that at a given distance, r, from a partially penetrating stress well, the response within an anisotropic aquifer would be the same as that at the distance $r(K_v/K_h)^{1/2}$ within an equivalent isotropic aquifer. The effects of vertical anisotropy, then, can be accounted for using this relationship, if the ratio of vertical to horizontal conductivity is known or can be estimated for the test formation.

FIELD TEST EXAMPLE

A slug interference test was conducted within the unconfined aquifer on the Hanford Site using a test configuration consisting of two observation wells and a stress well. The stress well (Well G) was completed within the lower third of the aquifer, while one observation well was completed within the lower section (Well F) and one within the upper section (Well E) of the aquifer. Fig. 4 presents pertinent information concerning the test-facility design. Detailed descriptions of the test and test analysis are provided in Spane (5) and Spane and Thorne (6).

[Place Fig. 4 Here]

Prior to initiating the slug interference test, the stress well casing was closed in at land surface using a wellhead assembly. The water column was then depressed approximately 10 m using gas supplied from compressed nitrogen gas cylinders. A constant gas pressure of about 100 kPa was maintained inside the well casing during the water-column depression phase to equilibrate heads in the well and aquifer system.

The slug interference test was initiated when the gas pressure within the well casing was released within about 1 second by simultaneously opening four ball valves on the wellhead assembly. The release of gas caused groundwater within the test interval to flow back inside the well casing, creating a slug withdrawal at the stress well. Pressure measurements were recorded at the stress well, and the slug interference response monitored at the two observation wells (Wells E and F). Discernible interference responses to the slug test were observed and recorded at both observation wells. Analysis of these responses is presented in the following section.

TEST ANALYSIS

Because of the small slug interference response (< 1 kPa) measured at the observation wells, test data were corrected for changes induced by barometric pressure fluctuations [Spane (5)]. These corrections were based on barometric efficiencies of the observation wells determined during the pretest period using the procedure described by Clark (12).

The observation-well test responses were analyzed by matching to type curves generated using the TYPCURV computer program described by Novakowski (4), which is based on fully penetrating wells within confined aquifers. As noted in Spane (5), the effects of partial penetration, anisotropy and delayed yield were not considered significant for the test data section analyzed. This conclusion was based on the observation-well distance/aquifer thickness relationship, and diagnostic pressure derivative analysis that was performed on the observed interference response. Further refinement of calculated transmissivity and storativity values would be expected, however, if these factors were taken into account.

The slug withdrawal test initiated at Well G caused a maximum slug interference pressure response of 0.64 kPa at Well E. The maximum response was recorded approximately 1,800 seconds after slug initiation. Figs. 5 and 6 show the slug interference response, and associated predicted responses for selected values of transmissivity and storativity, respectively. Selected values of transmissivity and storativity were used to illustrate the sensitivity of the analysis to varying parameter values.

[Place Fig. 5 and 6 Here]

Examination of Figs. 5 and 6 indicates that the slug pressure "hump," or "wave," was detected at approximately 300 seconds, with residual effects of the slug interference still manifested in the observation-well response up to 20,000 seconds. As indicated, the best fit for the observed slug interference response at Well E is obtained using a transmissivity value of 1.6×10^{-4} m^2/s and a storativity value of 4.4×10^{-3}.

At Well F, a maximum slug interference pressure response of 0.97 kPa was recorded approximately 650 seconds after slug initiation. Examination of Figs. 7 and 8 indicates that the slug pressure wave was first detected at approximately 75 seconds, with residual effects of the slug interference still evident in the observation-well response up to 4,000 seconds. This represents an earlier detection and slug interference dissipation by a factor of 4 to 5 in comparison to that recorded at Well E. The best fit for the observed slug interference response at Well F was obtained using a transmissivity value of 3.3×10^{-4} m^2/s and a storativity of 2.9×10^{-3}. The transmissivity value is approximately a factor of 2 higher than that obtained from analysis of test data for Well E, while the storativity value is nearly identical.

[Place Fig. 7 and Fig. 8 Here]

The transmissivity range determined from the slug interference test analysis compares favorably with results (2.1×10^{-4} to 3.7×10^{-4} m^2/s) obtained from a multiwell, constant-rate pumping test performed within the unconfined aquifer at a well test facility approximately 450 m away. Comparable transmissivity values (ranging from 1.3×10^{-4} to 3.3×10^{-4} m^2/s) also were obtained from single-well test analysis for the slug test data at stress Well G [Spane and Thorne (6)]. Less correspondence was exhibited with the results from previous single-well slug tests conducted at Wells E and F. These single-well tests resulted in transmissivity estimates of 2.2×10^{-4} to 5.6×10^{-5} m^2/s for Wells E and F, respectively. The difference in the test results, however, may be associated with the low stress levels used in the earlier tests. The maximum stress level for the previous tests was approximately 1/10 of that used during the slug interference test [Spane and Thorne (6)]. The calculated range for storativity (2.9×10^{-3} to 4.4×10^{-3}) is within the elastic response range commonly exhibited by unconfined aquifers.

CONCLUSIONS

Results of the field test evaluation indicate that slug interference testing is a viable hydrologic test method for characterizing shallow alluvial aquifers, and may be successfully employed for characterizing sites for which standard hydrologic test methods, such as single-well slug tests (for high transmissivity locations) and constant-rate pumping tests (for contaminated sites) are not applicable. Limitations in the area of investigation, however, restrict the application of slug interference tests to multiple-well sites with radial distances of $\leq$ 30 m.

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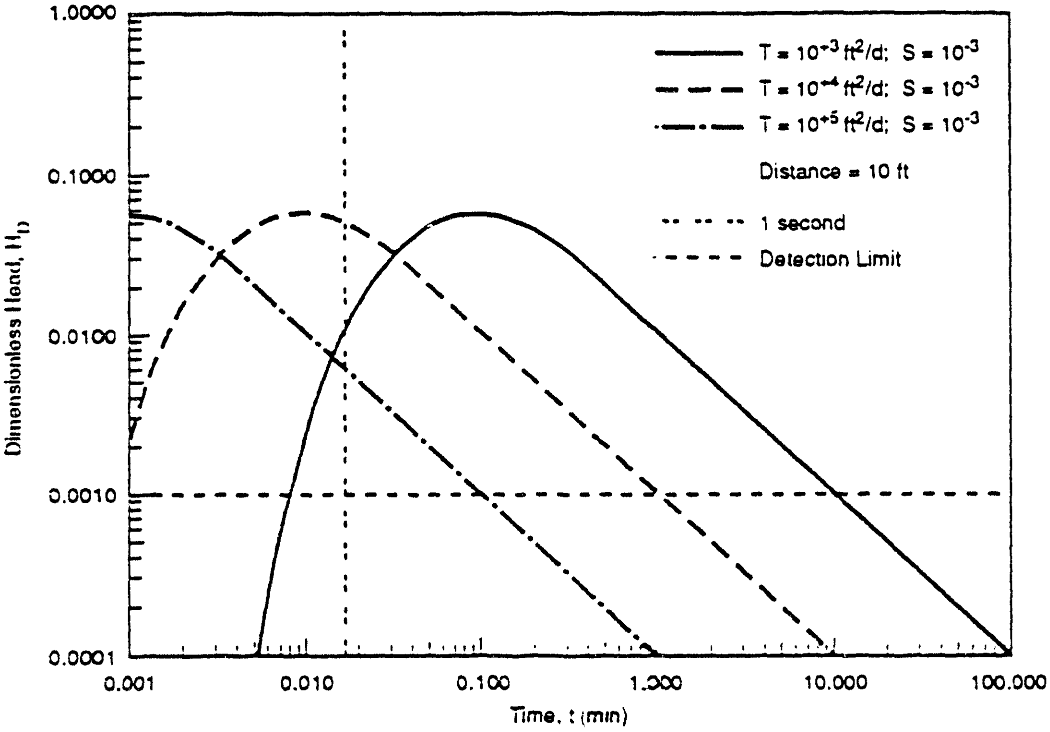

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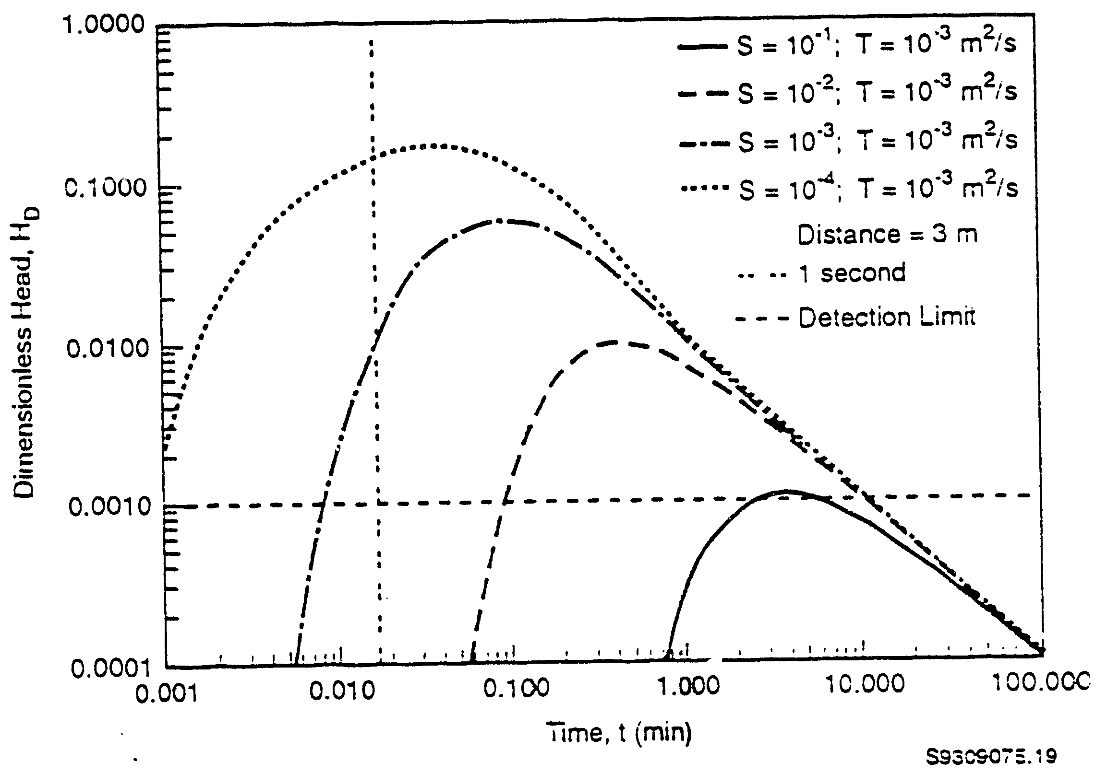
Fig. 1



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0.0100
0.0010
0.0001
Dimensionless Head, H_D
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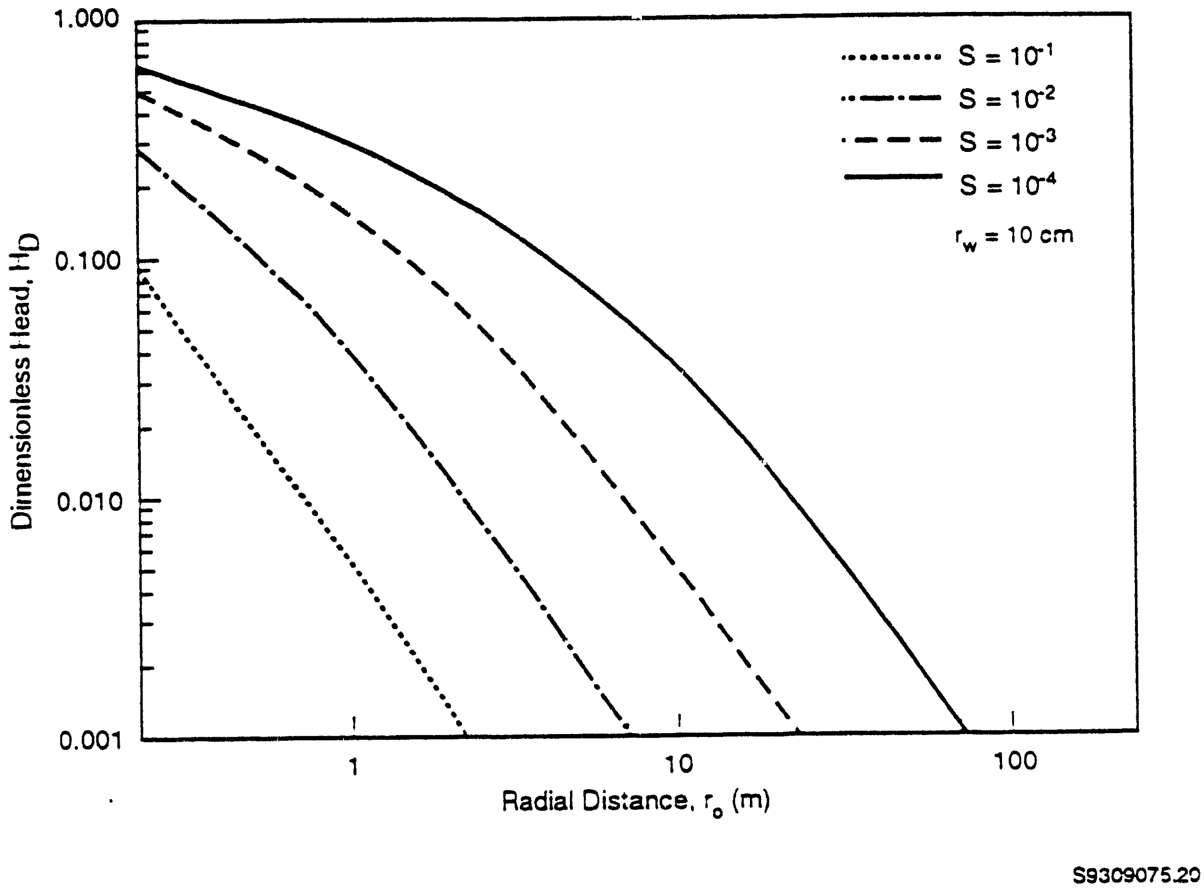
0.010
0.100
1.000
10.000
100.000
Time, t (min)
S = 10^{-1}; T = 10^{-3} m²/s
S = 10^{-2}; T = 10^{-3} m²/s
S = 10^{-3}; T = 10^{-3} m²/s
S = 10^{-4}; T = 10^{-3} m²/s
Distance = 3 m
1 second
Detection Limit
S9309075.19

Fig. 2



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0.010
0.001
1
10
100
Radial Distance, r_o (m)
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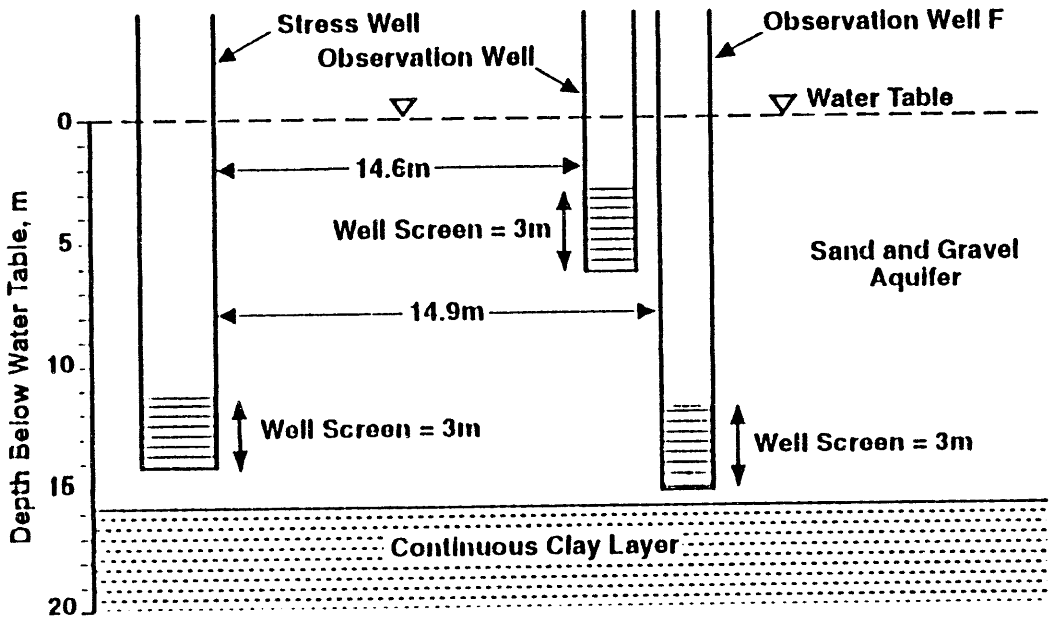
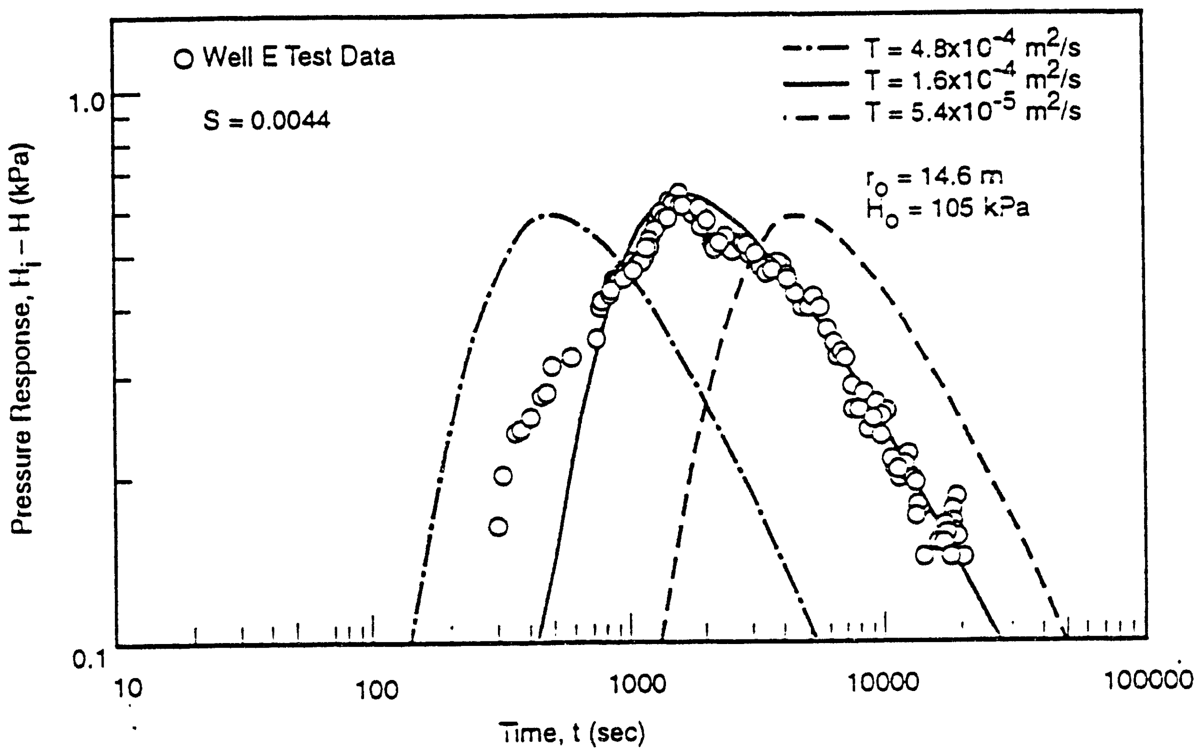
S = 10^{-2}
S = 10^{-3}
S = 10^{-4}
r_w = 10 cm
S9309075.20

Fig. 3



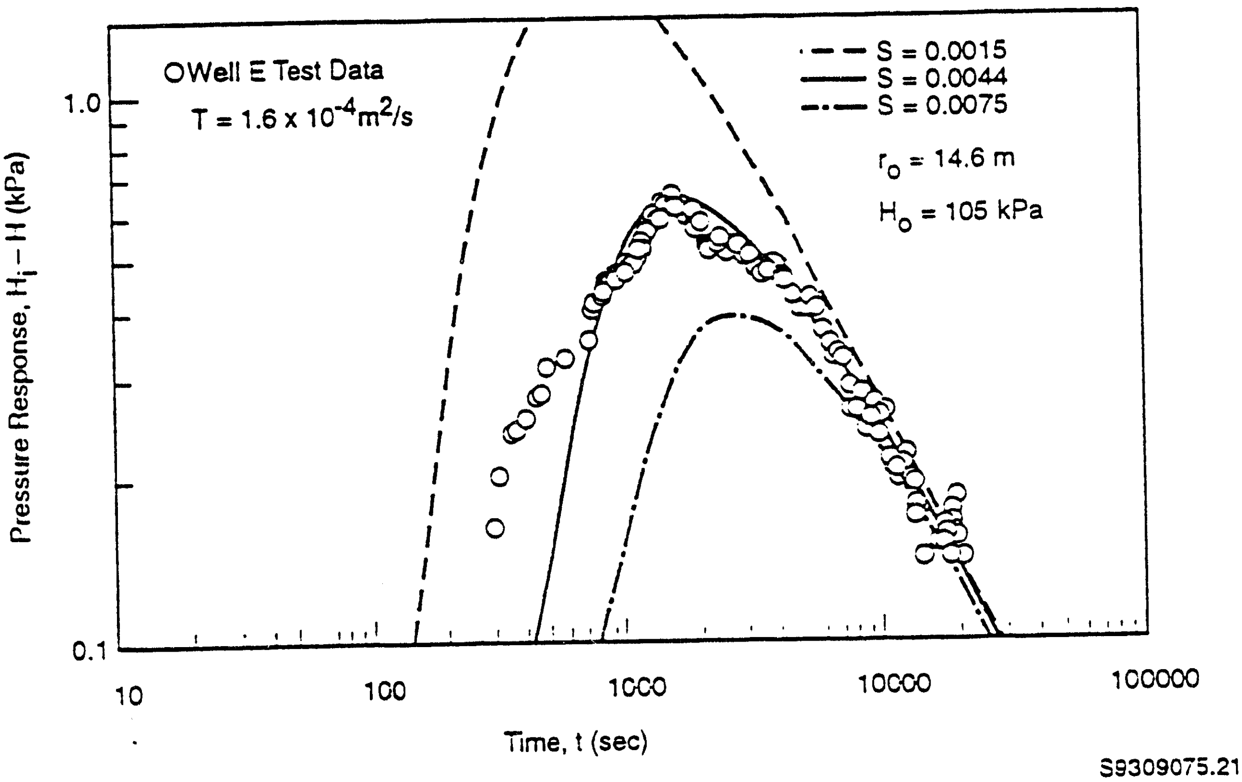
Schematic of slug interference test example relationships

S9309075.16



S9309075.23

Fig. 5



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S = 0.0044
S = 0.0075
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Ho = 105 kPa
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1000
10000
100000
Time, t (sec)
S9309075.21

Fig. 6

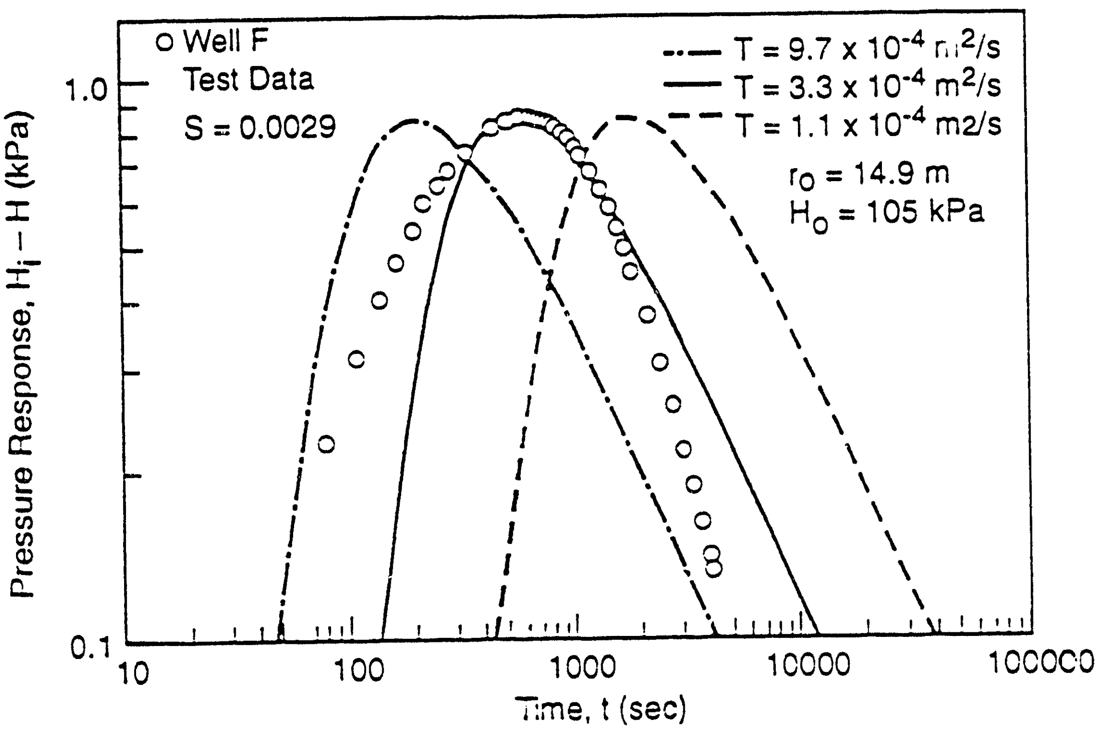

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Fig. 7

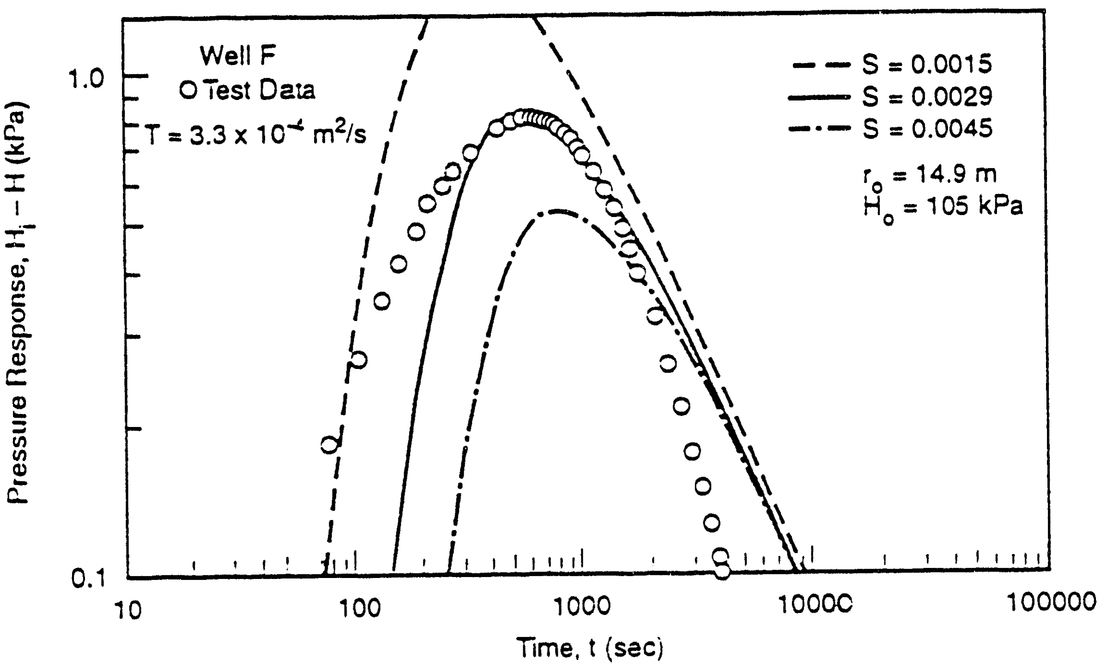

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Fig. 8

Applicability of Slug Interference Testing for Hydraulic Characterization of Contaminated Aquifer Sites

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L.C. Swanson
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Presentation Outline

- Factors inhibiting hydrogeologic characterization
- Standard hydraulic test methods
- Slug interference tests
  - Factors influencing test response
  - Test example
- Summary

Factors Inhibiting Characterization of Contaminated Areas

- Subsurface access limitations and/or restrictions
- Disposal of contaminated groundwater, soil, and geologic material
- Presence of high-permeability aquifers

Standard Hydraulic Test Methods

Test Method	Hydrologic Parameter
Slug injection/withdrawal	T, K
Constant-rate pumping	T, K, S, Sy
Slug interference	T, K, S, Sy

Slug Injection/Withdrawal Tests (Single Well)

- Advantages
  - Rapid results at low cost
  - No purge-water production
- Disadvantages
  - No characterization of moderate or high transmissive test intervals (i.e., $T > 10^3$ m^2/s)
  - Limited area of investigation

Constant-Rate Pumping Tests

- Advantage
  - Large area of investigation
  - Sensitive to test formation heterogeneities
  - Compatible with other hydrogeologic characterization activities
- Disadvantages
  - Costly and time-consuming
  - Large volumes of groundwater produced

Slug Interference Tests

- Advantages
  - Extended characterization capabilities
  - Characterization of interwell distances to ~ 30 m
  - Rapid results at low cost
  - No purge-water production
- Disadvantages
  - Limited characterization area
  - Analytical constraints

Factors Influencing Test Response

- Transmissivity
- Storativity
- Radial distance
- Partial penetration
- Anisotropy
- Wellbore storage

Summary – Slug Interference Testing

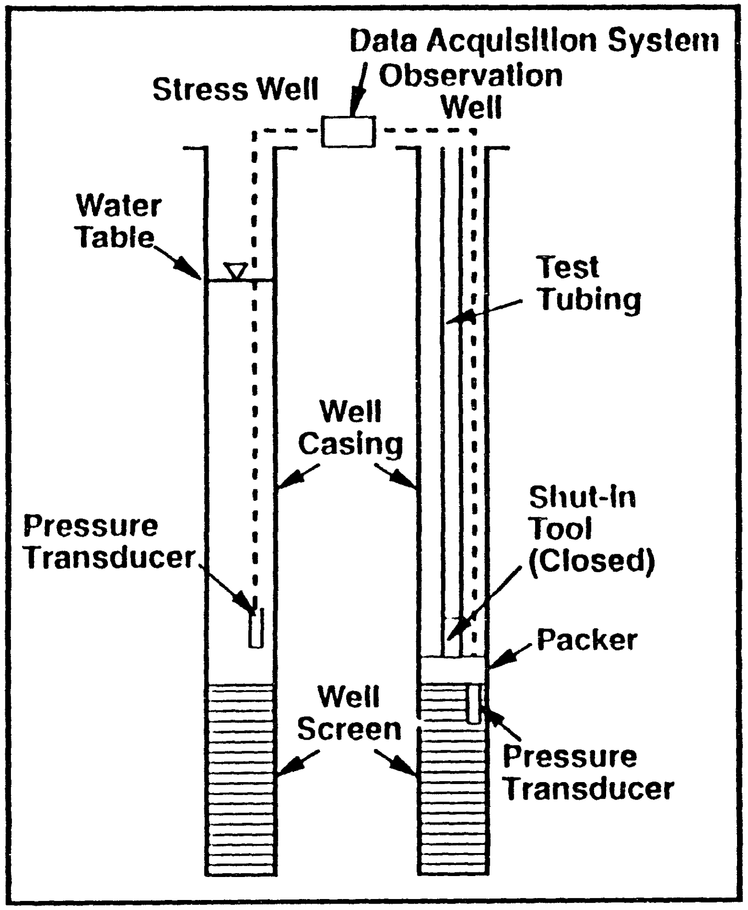
- Extended hydraulic characterization capabilities
- Rapid results at low cost
- Characterization of interwell distances to ~ 30 m

Areas of Future Emphasis

- Modify existing slug-interference analytical method to account for the effects of
  - Partial penetration
  - Anisotropy
  - Unconfined aquifer conditions

Water Table Above Well Screen

Well Completion and Test Equipment Details for Slug Interference Test System Configuration Where Water Table Is Above Well Screen



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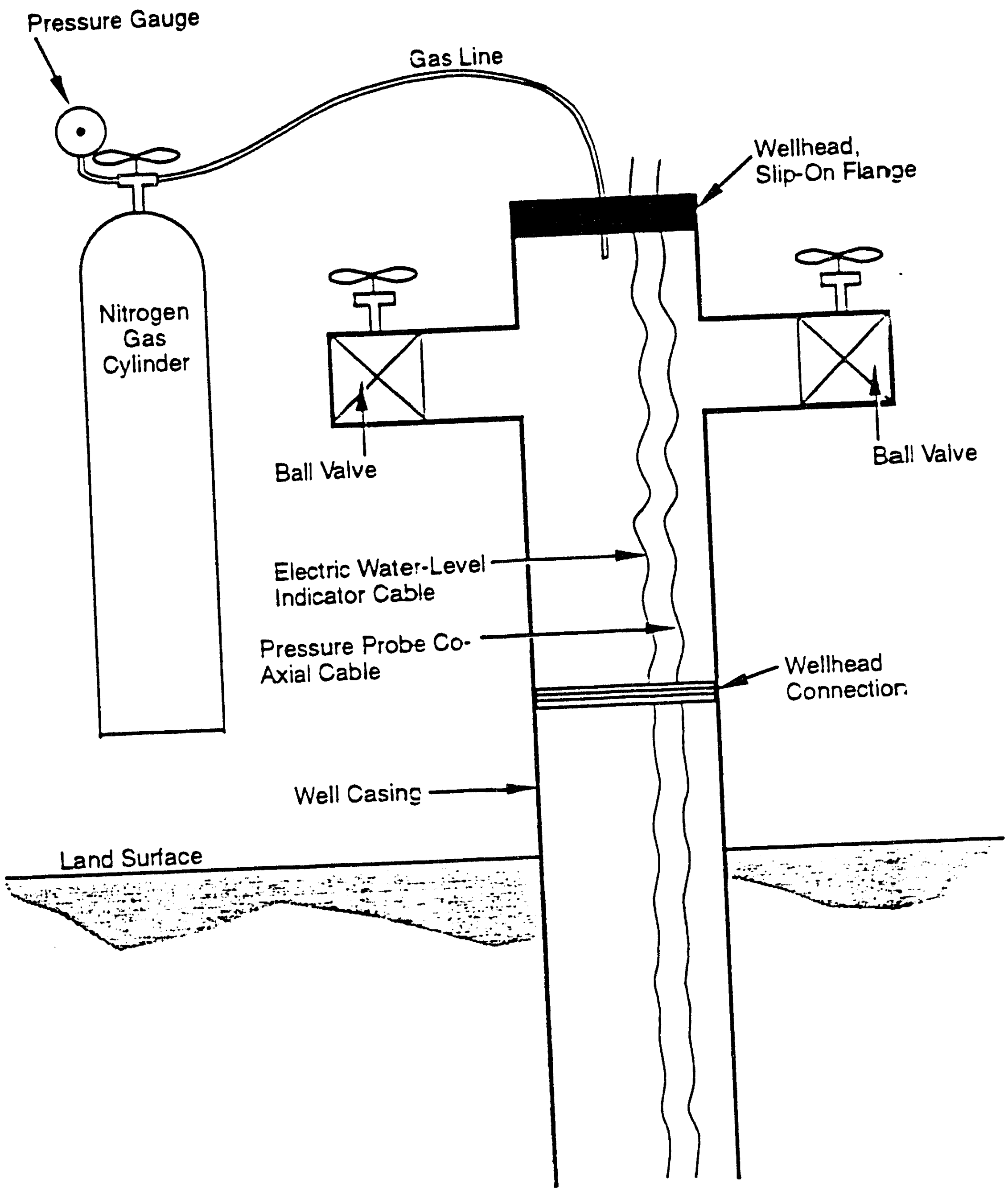
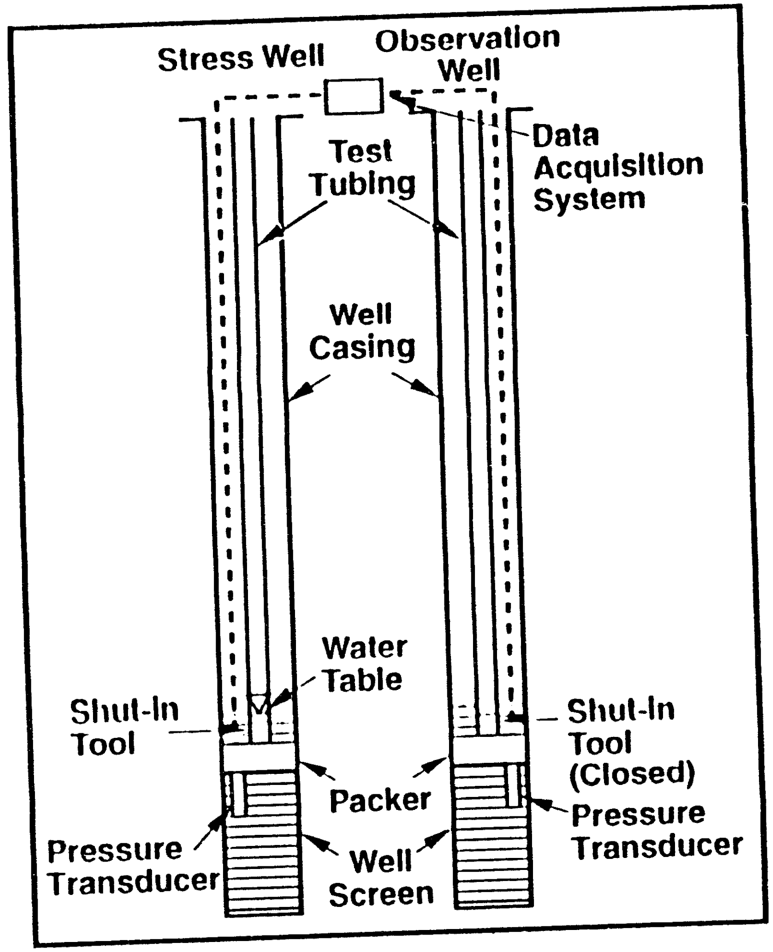

Pressure Gauge
Gas Line
Wellhead,
Slip-On Flange
Nitrogen
Gas
Cylinder
Ball Valve
Ball Valve
Electric Water-Level
Indicator Cable
Pressure Probe Co-
Axial Cable
Wellhead
Connection
Well Casing
Land Surface

S9309075.17

Water Table Within Well Screen

Well Completion and Test Equipment Details for Slug Interference Test System Configuration Where Water Table Is Within Well Screen



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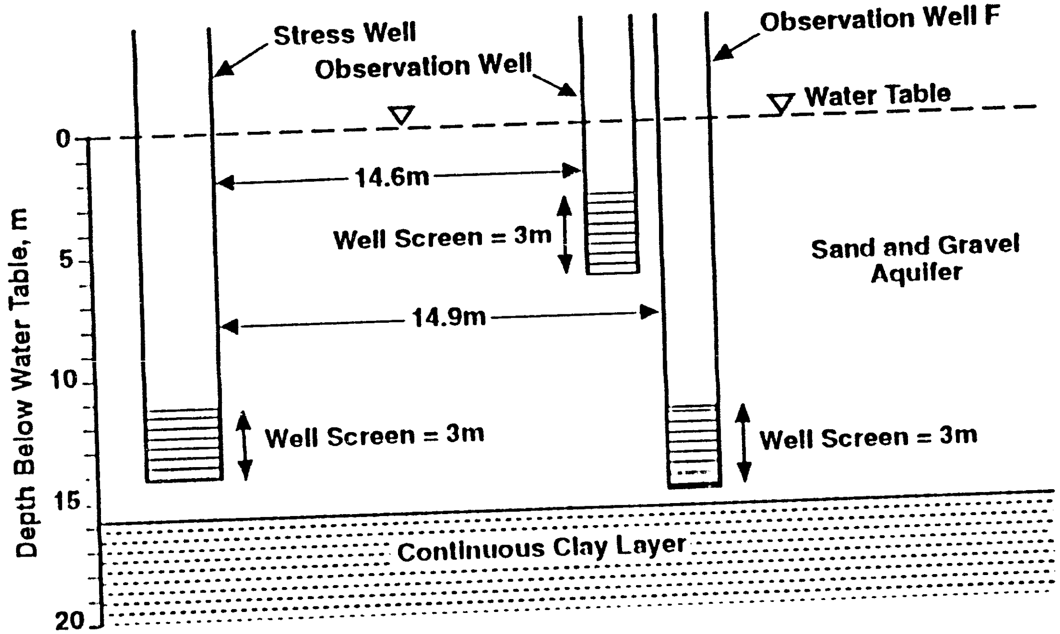
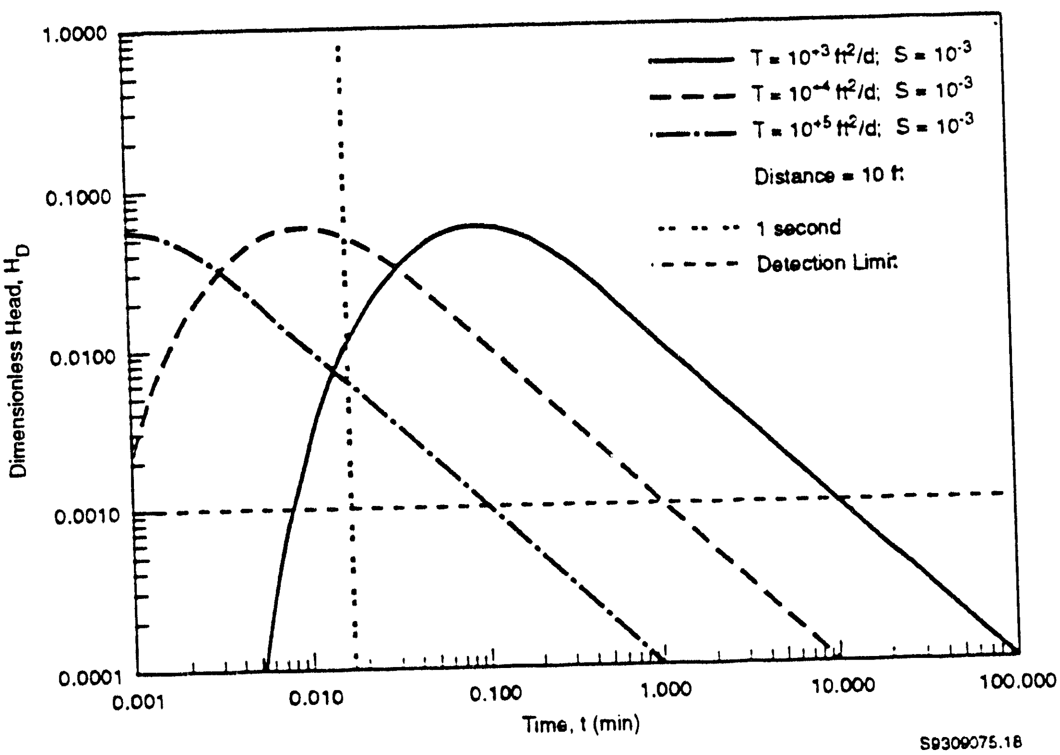


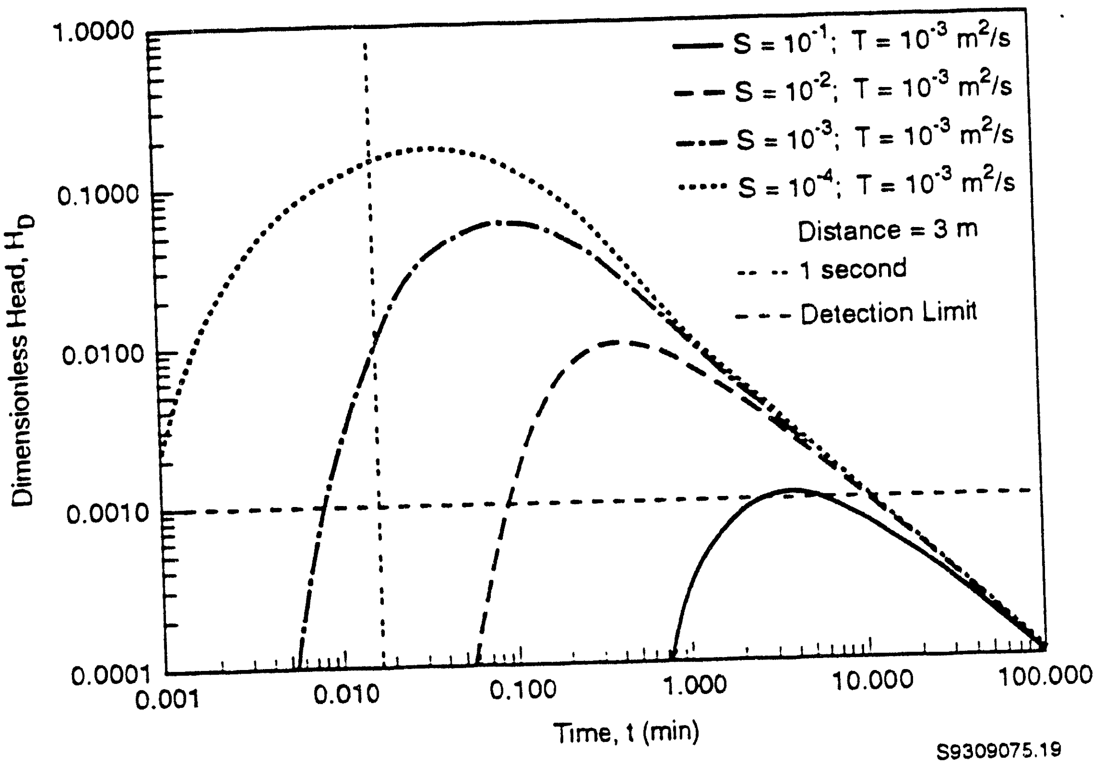
Schematic of slug interference test example relationships

S9309075.16



1.0000
0.1000
0.0100
0.0010
0.0001
Dimensionless Head, H_D
0.001
0.010
0.100
1.000
10.000
100.000
Time, t (min)
T = 10^{+3} ft²/d; S = 10^{-3}
T = 10^{+4} ft²/d; S = 10^{-3}
T = 10^{+5} ft²/d; S = 10^{-3}
Distance = 10 ft
1 second
Detection Limit

S9309075.18



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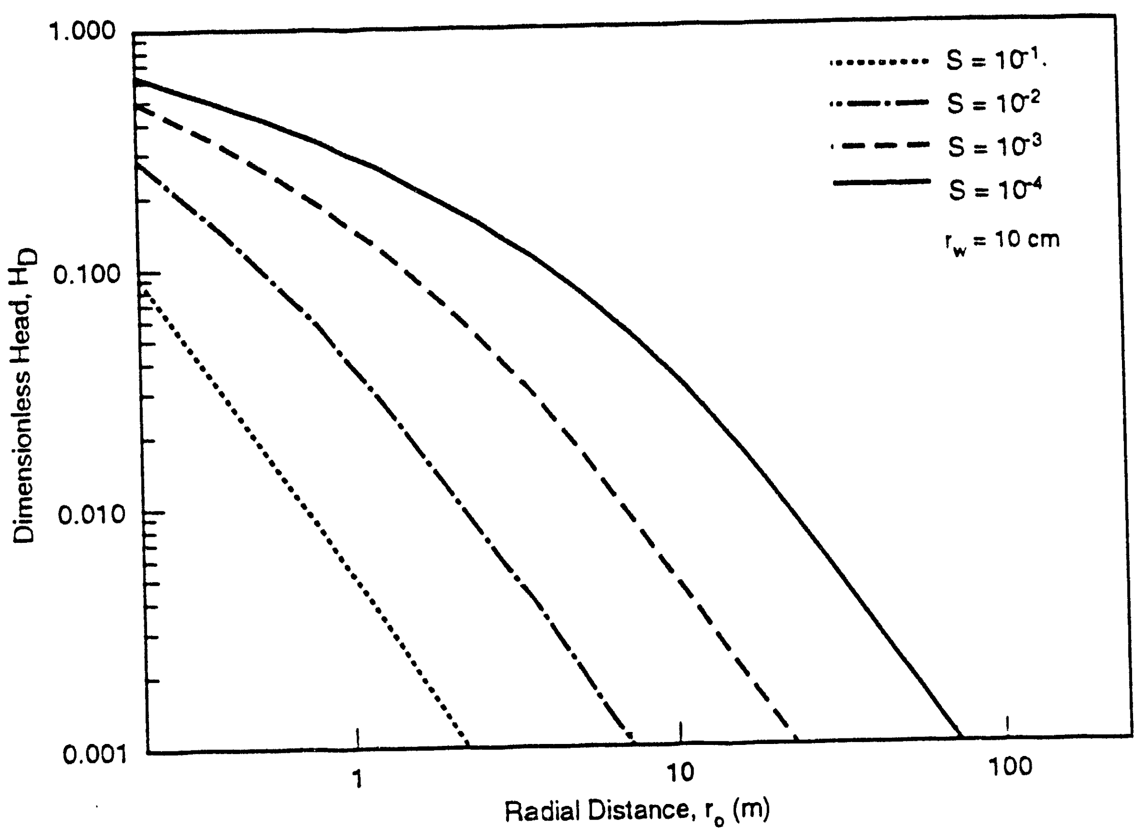
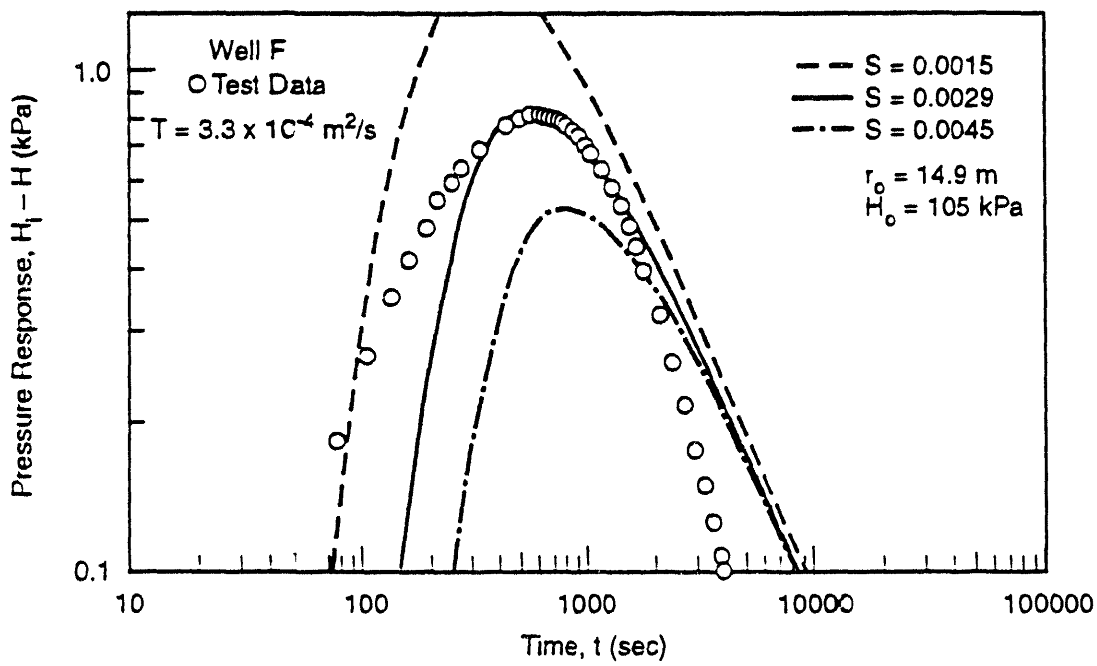
S = 10^-2; T = 10^-3 m^2/s
S = 10^-3; T = 10^-3 m^2/s
S = 10^-4; T = 10^-3 m^2/s
Distance = 3 m
1 second
Detection Limit
Dimensionless Head, H_D
1.0000
0.1000
0.0100
0.0010
0.0001
0.001
0.010
0.100
1.000
10.000
100.000
Time, t (min)

S9309075.19

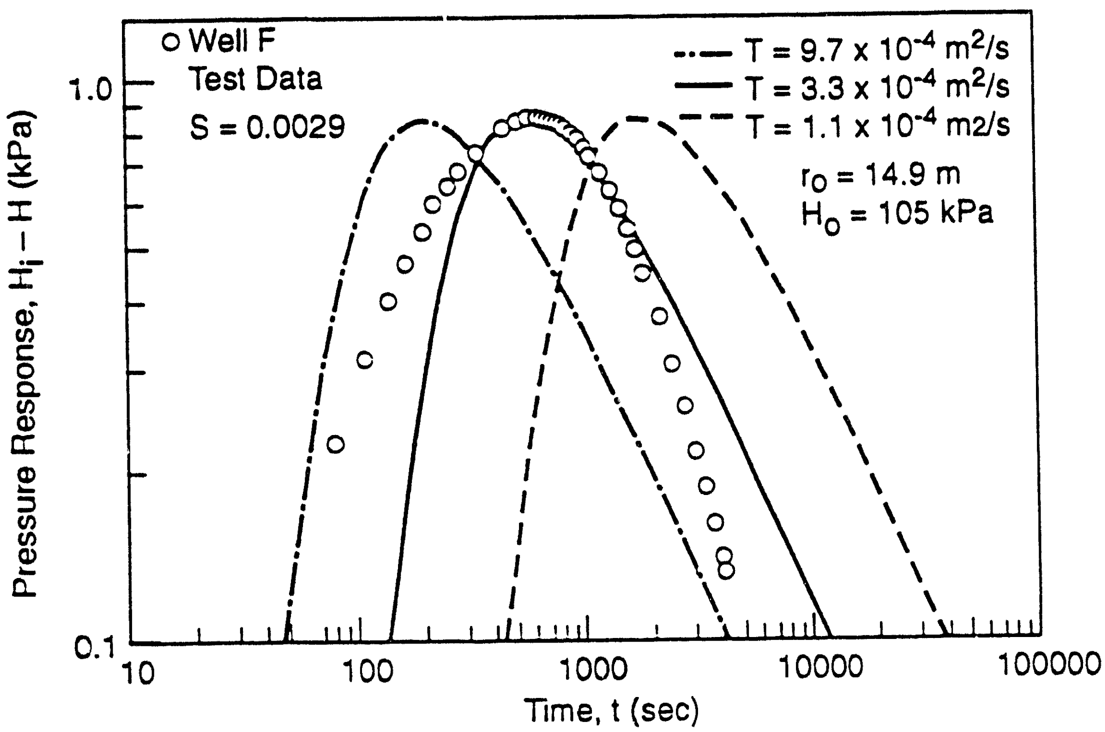


Dimensionless Head, H_D
1.000
0.100
0.010
0.001
1
10
100
Radial Distance, r_o (m)
$S = 10^{-1}$
$S = 10^{-2}$
$S = 10^{-3}$
$S = 10^{-4}$
r_w = 10 cm

SS309075.20

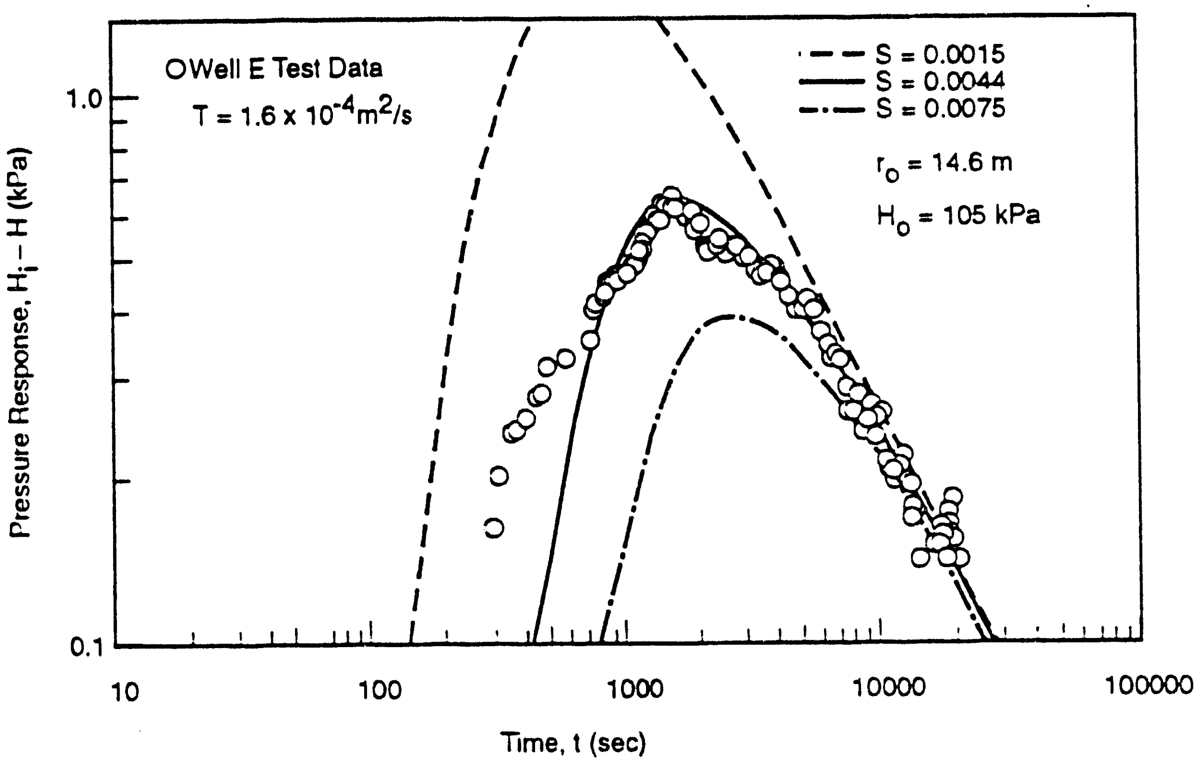

Well F
O Test Data
T = 3.3 x 10⁻⁴ m²/s
S = 0.0015
S = 0.0029
S = 0.0045
r_o = 14.9 m
H_o = 105 kPa
Pressure Response, H_i – H (kPa)
1.0
0.1
10
100
1000
10000
100000
Time, t (sec)

S9309075.12



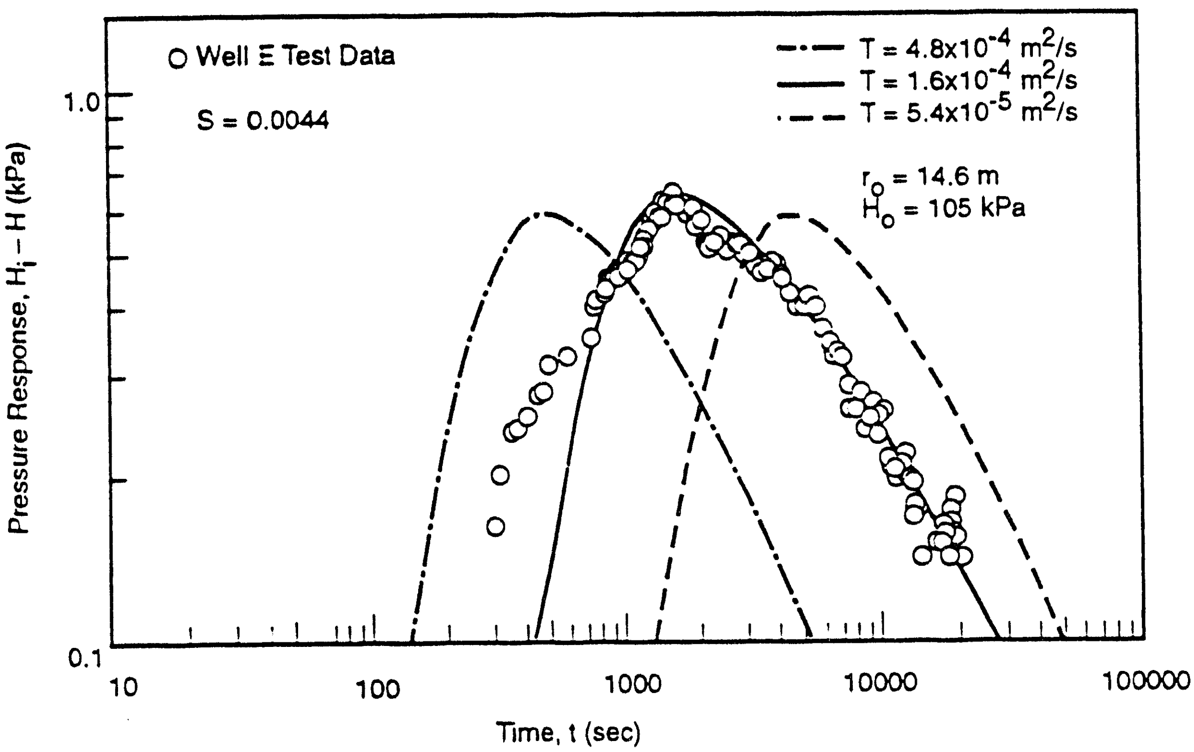
Pressure Response, H_i – H (kPa)
1.0
0.1
10
100
1000
10000
100000
Time, t (sec)
o Well F
Test Data
S = 0.0029
T = 9.7 x 10^-4 m^2/s
T = 3.3 x 10^-4 m^2/s
T = 1.1 x 10^-4 m2/s
r_o = 14.9 m
H_o = 105 kPa

S9309075.22



OWell E Test Data
T = 1.6 x 10-4m2/s
S = 0.0015
S = 0.0044
S = 0.0075
ro = 14.6 m
Ho = 105 kPa
1.0
0.1
Pressure Response, Hi – H (kPa)
10
100
1000
10000
100000
Time, t (sec)

S9309075.21



O Well Ξ Test Data
S = 0.0044
T = 4.8x10^-4 m^2/s
T = 1.6x10^-4 m^2/s
T = 5.4x10^-5 m^2/s
r_o = 14.6 m
H_o = 105 kPa
Pressure Response, H_i – H (kPa)
1.0
0.1
10
100
1000
10000
100000
Time, t (sec)

S9309075.23

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END