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ABSTRACT

Slug interference tests are conducted by instantaneously changing the water level in a well and monitoring the aquifer response at one or more observation wells. The applicability of this method for hydraulic characterization of a high permeability unconfined aquifer at the Hanford Site was evaluated. Analytical techniques were used to predict slug interference responses over a range of aquifer hydraulic conditions and observation well distances. This was followed by a field test of the proposed technique. The results showed that slug interference testing can be used to characterize aquifers having transmissivities up to 10^{-1} m^2/s compared to a maximum transmissivity of about 10^{-3} m^2/s for single-well slug tests. The amplitude of the pressure response measured at the observation well is primarily determined by aquifer storativity, while the time-lag of the pressure peak is mainly controlled by the transmissivity. Several recommendations are made optimizing the results of slug interference tests in higher permeability, unconfined to semiconfined aquifers.

INTRODUCTION

Aquifer hydraulic properties, particularly transmissivity, T, and storativity, S, are important in determining ground-water velocity and travel-times of hazardous radioactive and chemical contaminants. Aquifer pumping tests generally provide the best information on hydraulic properties. However, pumping tests are sometimes not possible at hazardous waste sites because of problems with disposal of the contaminated ground water removed during the test. Partly for this reason, the slug test[1] has become a popular method for determining hydraulic properties at contaminated sites. Single-well slug tests conducted in high permeability formations, however, are often not analyzable and can give only a lower limit for transmissivity.

A need clearly exists to develop test methods that can be used to accurately characterize high permeability aquifers without removing large amounts of contaminated ground water. One test method that appears to hold particular promise for characterizing such sites is the slug interference

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test. Slug interference testing has been utilized in the past[2] primarily for characterizing confined formations having low storativities ($10^{-6} < S < 10^{-4}$). The objective of this study was to evaluate the applicability of slug interference testing in a relatively high permeability unconfined or semi-confined aquifer with storativity values ranging between 10^{-4} and 10^{-1}.

Parts of the upper aquifer at the Hanford Site are within unconsolidated sands and gravels of the Hanford formation (informal designation) deposited by both normal and catastrophic glaciofluvial processes. This aquifer is generally unconfined with transmissivity values ranging up to 10^{-1} m^2/s.[3] Results from single-well slug tests are usually not analyzable if the transmissivity is higher than 10^{-3} m^2/s.[4] To assess the applicability of slug interference testing of the Hanford formation, a two phase investigation was conducted. The first phase included an analytical prediction of slug interference test responses over the expected range of aquifer hydraulic conditions at the Hanford Site. The second phase consisted of a field test and a comparison of analysis results with previously conducted hydraulic characterization tests.

TEST AND ANALYSIS METHOD

Slug tests are normally performed by instantaneously raising or lowering the water level (head) in a well and monitoring recovery to static formation conditions in the same well. Transmissivity and, theoretically, storativity can then be calculated by matching the water-level response to dimensionless type curves. However, the storativity value calculated from a single-well slug test is generally not reliable.[1] Figure 1 shows a typical response for a single-well slug test. The dimensionless head, H_D, is defined as the difference between the head at time t and the pretest head, divided by the maximum head change for the test.

The slug interference test requires a minimum of two wells in relatively close proximity in the same aquifer. The maximum distance is about 30 m, depending on site conditions. An instantaneous increase or decrease in head is initiated at the stress well, and the associated formation pressure response is monitored at the observation well. Analysis of the observation well response provides estimates of formation transmissivity and storativity. Unlike single-well tests, storativity values determined from slug interference testing are usually reliable.

Novakowski[5] presented a FORTRAN program that can generate slug interference type curves based on the analytical solutions and boundary conditions presented by Cooper et al.[1] This analytical solution is strictly valid only for a fully penetrating well in a confined aquifer. However, it yields acceptable results for partially penetrating wells and unconfined aquifer tests provided that the saturated thickness of the unconfined aquifer does not change significantly and radial flow conditions are dominant (i.e., no significant vertical flow components). The effects of partial penetration and unconfined aquifer conditions on slug interference tests are discussed in depth in the project report.[4]

A modified version of Novakowski's program was used to predict slug interference responses and to match the results of the field test. The original program was modified to allow increased density of generated type-curve data points, to extend the lower limit of dimensionless head, and to provide additional test description information in the computer file output. To validate the modified program, slug test responses were generated and compared to type-curve examples for the stress well[1] and for slug interference responses at the observation well.[6] The generated responses matched the published type curve data to within 3 or 4 significant decimal places for dimensionless head.

ANALYTICAL ASSESSMENT

The modified version of the Novakowski[5] computer program was used to predict responses at specified distances from the stress well and over a range of transmissivity and storativity conditions. Transmissivities were varied from 10^{-3} to 10^{-1} m^2/s and storativities were varied from 10^{-4} to 10^{-1}. Observation well distances of 3.0, 7.6, 15.2, and 30.5 m were considered.

Results of the analytical assessment indicated that for the storativity range considered to be most representative of the unconfined aquifer on the Hanford Site (10^{-2} to 10^{-3}) and for transmissivities ranging up to 10^{-1} m^2/s, slug interference responses should be observable to maximum distances of between 10 and 33 m from the stress well.[4] Other conclusions from the analytical assessment of slug interference responses include:

- o Higher transmissivity is associated with faster peak response (less time-lag) at the observation well.
- o Formation storativity is the primary hydrogeologic factor controlling the amplitude of the observed interference response.
- o Amplitude of the interference response diminishes rapidly with distance from the stress well.
- o Wellbore storage at the stress well (slug volume) has a significant influence on the amplitude of the interference response and should be designed to be as large as possible.
- o Wellbore storage in the observation well has a dampening effect on slug interference amplitude and arrival time, and should be minimized.

Figure 2 shows the predicted slug interference responses at an observation well distance of 3.0 m for aquifer transmissivities of 10^{-3}, 10^{-2}, and 10^{-1} m^2/s and aquifer storativity of 10^{-3}. As indicated, at a given observation distance, transmissivity has no effect on the magnitude of test response, but does exert a strong influence on the time required for the pressure peak to occur. Figure 3 shows the predicted slug test response at an observation well 3.0 m from the stress well, for storativities of 10^{-1}, 10^{-2}, 10^{-3}, and 10^{-4}, and a transmissivity of 10^{-3} m^2/s. As shown, the amplitude of the slug response at the observation well is strongly influencea by the storativity of the aquifer.

Figure 4 shows the predicted maximum slug interference response as a function of distance from the stress well for storativities ranging from 10^{-1} to 10^{-4}. A wellbore radius of 10 cm was assumed. As expected, smaller distances to the observation well and lower storativity values increase the magnitude of the observation well response. For the storativity range considered to be representative of most unconfined aquifer conditions on the Hanford Site (i.e., 10^{-2} to 10^{-3}), slug interference responses should be observable to maximum distances between 10 and 30 m from the stress well.

Significant wellbore storage in the observation well tends to cause the well response to be lagged and attenuated from the predicted response, which assumes that wellbore storage is negligible. A graphical method has been presented[2] for analyzing slug interference responses both for cases where the wellbore storage at the observation well is, and is not, significant.

FIELD TEST EVALUATION

Based on the results of the analytical assessment, a slug interference field test was designed and conducted. The test site had two existing wells, designated E and F, that had previously been characterized by single-well slug tests. These were used as observation wells. A new well (G) was drilled within 16 m of the two existing wells and was used as the stress well. Wells E and F were 14.6 m and 14.9 m, respectively, from the stress well.

Equipment and Procedures

The well configurations and test equipment installed in the observation wells are illustrated in Figure 5. Inflatable packers were installed immediately above the well screen to minimize wellbore storage. Quartz pressure transducers were installed downhole to measure the pressure in the test zone. Transducers with a resolution of 0.01 kPa were required to measure the small expected pressure changes.

To create the maximum possible slug volume change, and enable an instantaneous pressure change to be implemented, a pneumatic system was built which used compressed nitrogen to depress the water level in the stress well. The configuration of the stress well and the installed test equipment are shown in Figure 6.

Upon reaching the desired depth at the stress well, a temporary well screen was installed, a pressure transducer was placed near the bottom of the well, and a specially built wellhead assembly was welded to the top of the casing. The transducer cable passed through a compression fitting on the wellhead that provided an air-tight seal. The wellhead also had a pressure gauge, an air hose connection and four, 4-in.-diameter ball valves that allowed gas pressure to be released very quickly from the well casing. The air hose was connected to a bottle of compressed nitrogen through a pressure regulator.

The water level in the well was depressed by pressurizing the well casing with nitrogen gas to about 105 kPa. This selected pressure was designed to depress the water level within the stress well approximately 10.7 m below the static level. The gas pressure was maintained inside the well casing for about 17 hrs to equilibrate the well and formation pressures. During this time, the gas pressure was kept constant by the regulator and any gas lost through leakage was automatically replaced from the nitrogen bottle. The injection of displaced water into the test formation resulted in detectable pressure changes at both observation wells. The pressures were allowed to stabilize at static formation conditions before initiating the slug test.

The slug interference test was initiated by abruptly releasing the gas pressure within the well casing at the stress well. The pressure was released in about 1 second by simultaneously opening the four, 4-in. ball valves on the well head assembly. The release of gas caused ground water within the test interval to flow back inside the well casing, thus creating a slug withdrawal at the str‹‹s well. Pressure measurements were recorded at the stress well and at th‿ wo observation wells. Discernable pressure responses for the slug test were observed at both observation wells.

Field Test Results

Because of the very small slug interference responses (<1 kPa) measured at the observation wells, the pressure data were corrected for changes induced by barometric pressure fluctuations.[4] This correction was based on barometric efficiencies[7] of the observation wells determined during the pre-test period.

To determine aquifer transmissivity and storativity from the observation well responses, the barometric-corrected data were compared to theoretical responses generated using the modified version of Novakowski's computer program[5]. The barometric-corrected pressure response at observation well E is shown in Figure 7. The best fitting predicted response corresponds to a transmissivity of 1.6×10^{-4} m^2/s and a storativity of 4.4×10^{-3}. To demonstrate the sensitivity to varying storativity, predicted responses are also shown assuming storativity values of 1.5×10^{-3} and 7.5×10^{-3}.

Barometric-corrected pressure response at observation well F is shown in Figure 8. The best fitting predicted response corresponds to a transmissivity of 3.3×10^{-4} m^2/s and a storativity of 2.9×10^{-3}. To demonstrate the sensitivity to varying transmissivity, predicted responses are also shown assuming transmissivity values of 1.1×10^{-4} and 9.7×10^{-4}.

The transmissivity range determined from slug interference analysis compares favorably with the results of a single-well test analysis of the data from the stress well. The single-well analysis resulted in transmissivity between 1.3×10^{-4} and 3.3×10^{-4} m^2/s. Less correspondence is exhibited with the results of previous single-well slug tests conducted at the observation wells. The single-well tests resulted in transmissivity estimates of 2.2×10^{-4} and 5.6×10^{-5} m^2/s for wells E and F, respectively. The difference in the test results may be related to the low stress levels used in the earlier tests. The maximum head change was about 1/10 of that utilized during the slug interference test. The calculated storativity values suggest semi-confined conditions, but are also within the elastic response range commonly exhibited by unconfined aquifers.

The transmissivity at the test site was not in the range of 0.01 to 0.1 m^2/s for which this method is expected to be most useful. For the existing site conditions, conventional slug tests can also be used to obtain estimates of transmissivity. However, the slug interference test technique provided comparable estimates for hydraulic property estimates (i.e., hydraulic conductivity), and made it possible to calculate storativity for the intervening test formation.

CONCLUSIONS

Based on both the analytical assessment and the field test, it appears that slug interference testing may be a useful tool for characterizing higher permeability aquifers such as the unconfined Hanford formation. The biggest disadvantage of this method is the need for two wells close together in the same aquifer. The following recommendations were developed for conducting slug interference tests in higher permeability, unconfined aquifers.

- Wellbore storage of the observation well should be minimized by isolating the observation well test interval with downhole packer(s).
- The stress well head change should be at least 7.6 m of water and the slug volume should be maximized by using the largest diameter well possible.
- Relatively frequent and sensitive pressure measurements are required in the observation well to detect the slug interference response.
- External stresses which may affect the measured pressures in the observation well should be determined and removed. These stresses may include barometric pressure changes or the effects of nearby pumping.

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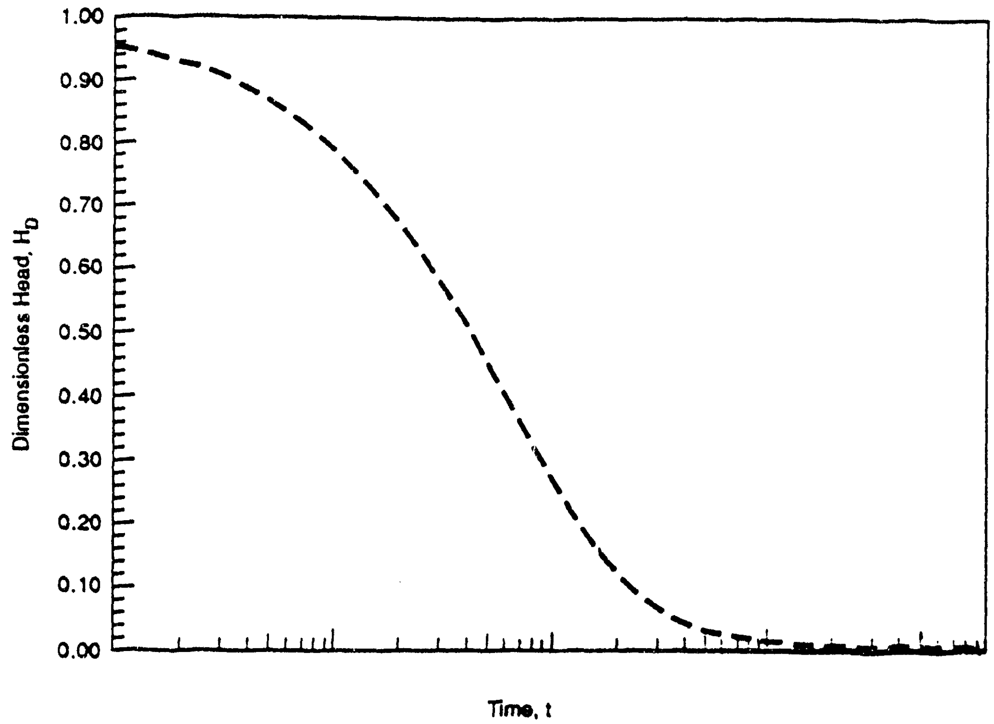

Figure 1 - Typical single-well slug test.

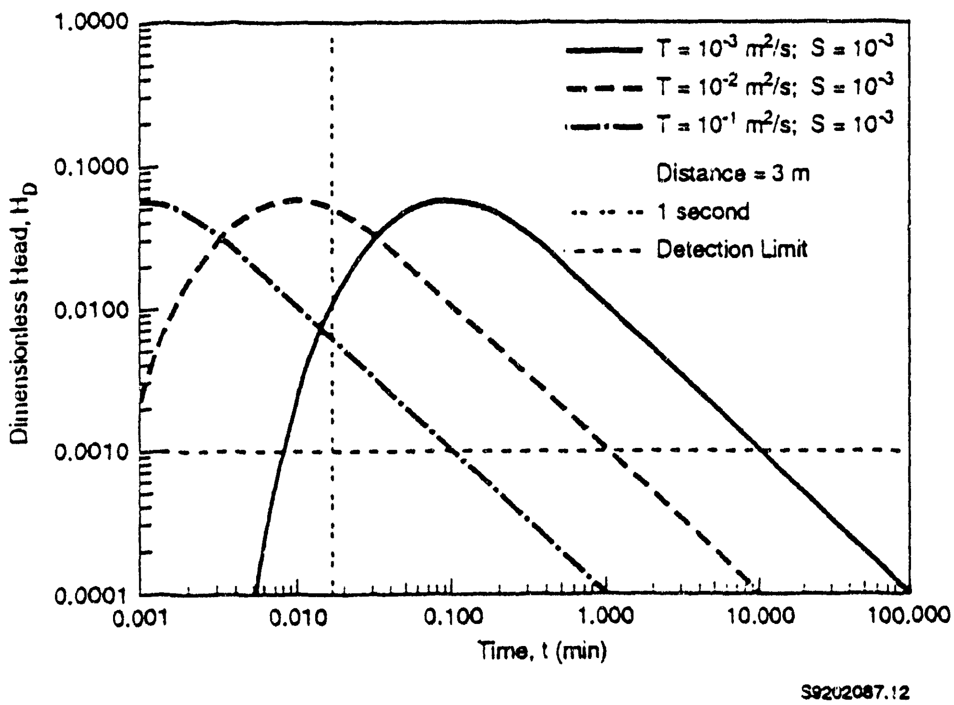

Figure 2 - Predicted slug-interference responses for various transmissivities.

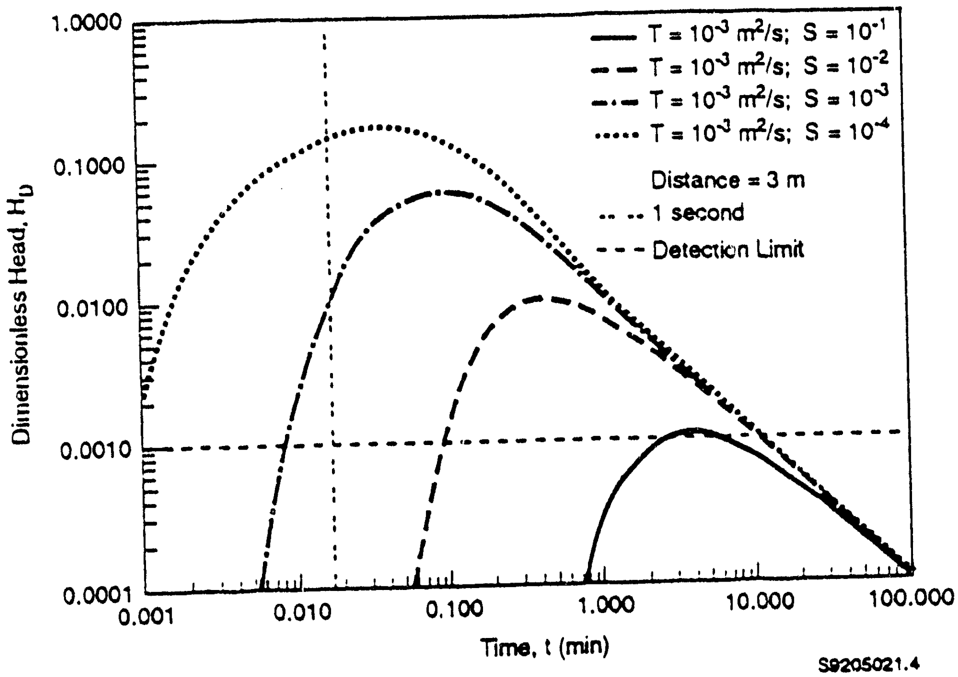

Figure 3 - Predicted slug-interference responses for various storativities.

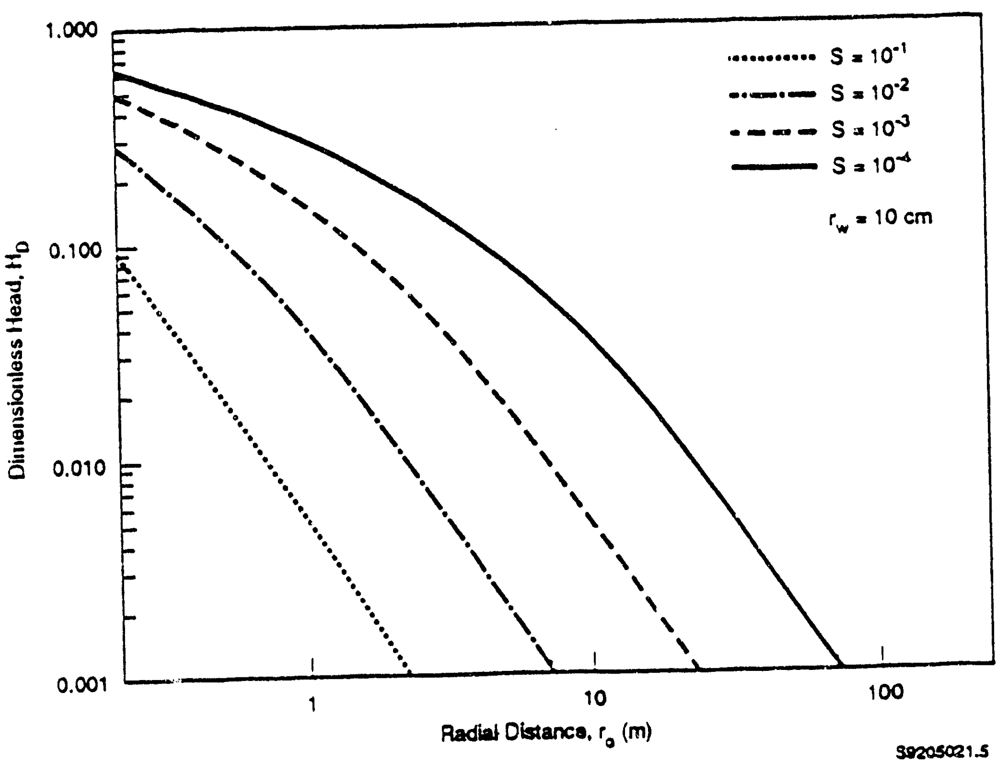

Figure 4 - Predicted maximum slug interference test response as a function of distance.

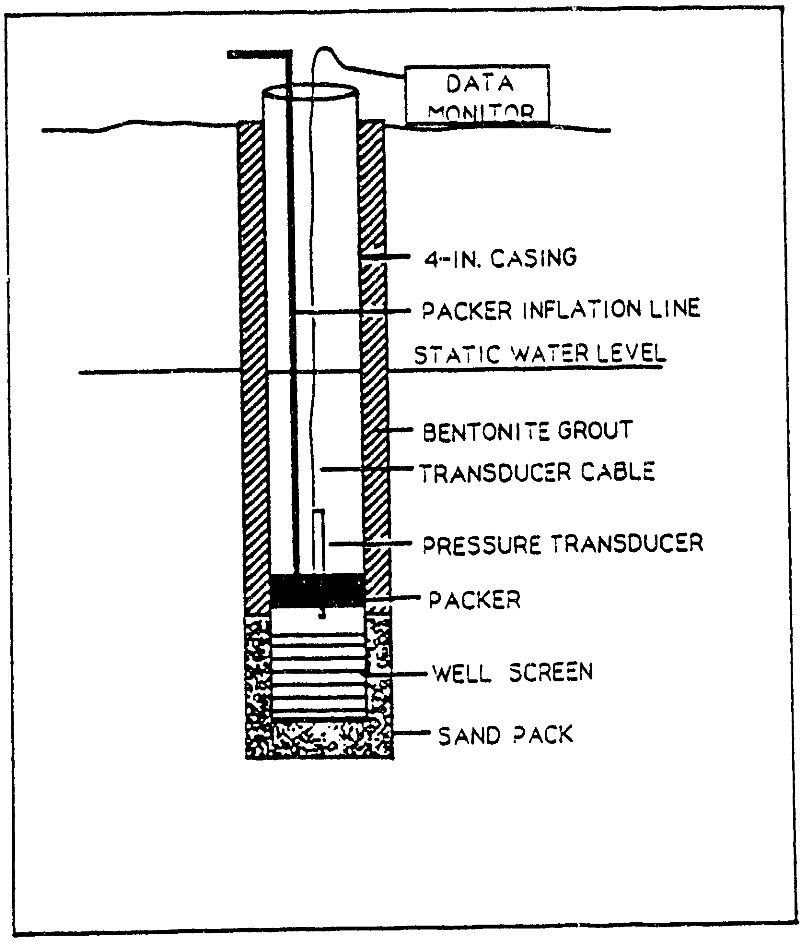

Figure 5 - Borehole configuration and test equipment for observation wells E and F.

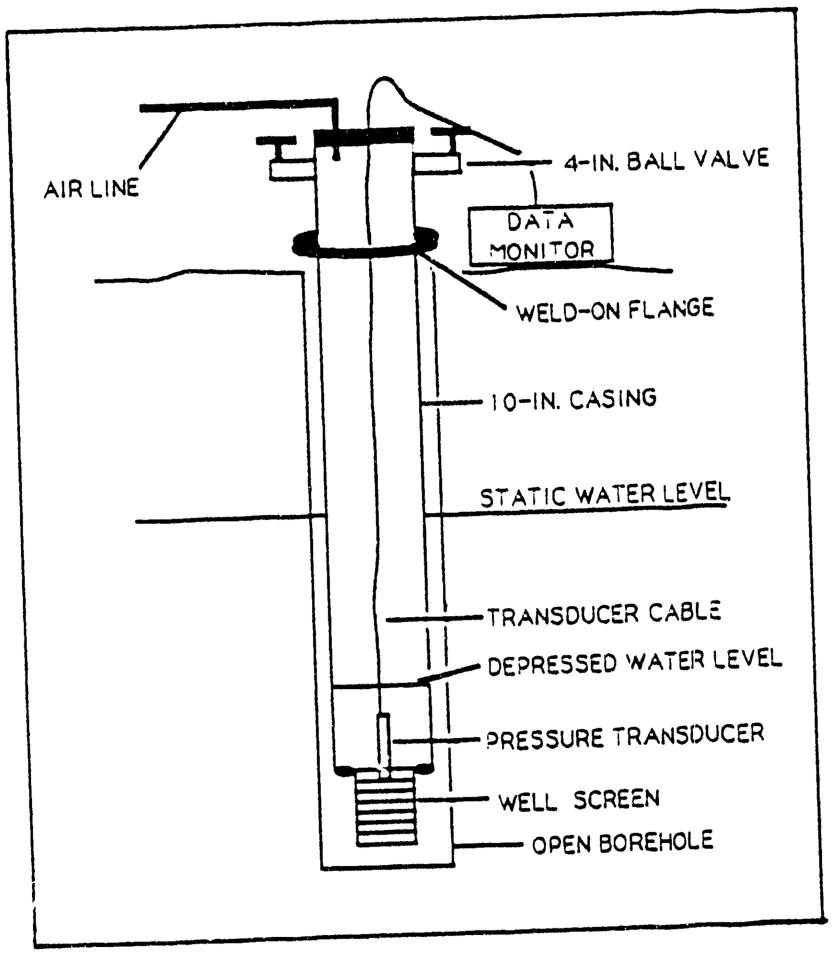

Figure 6 - Borehole configuration and test equipment for the stress well.

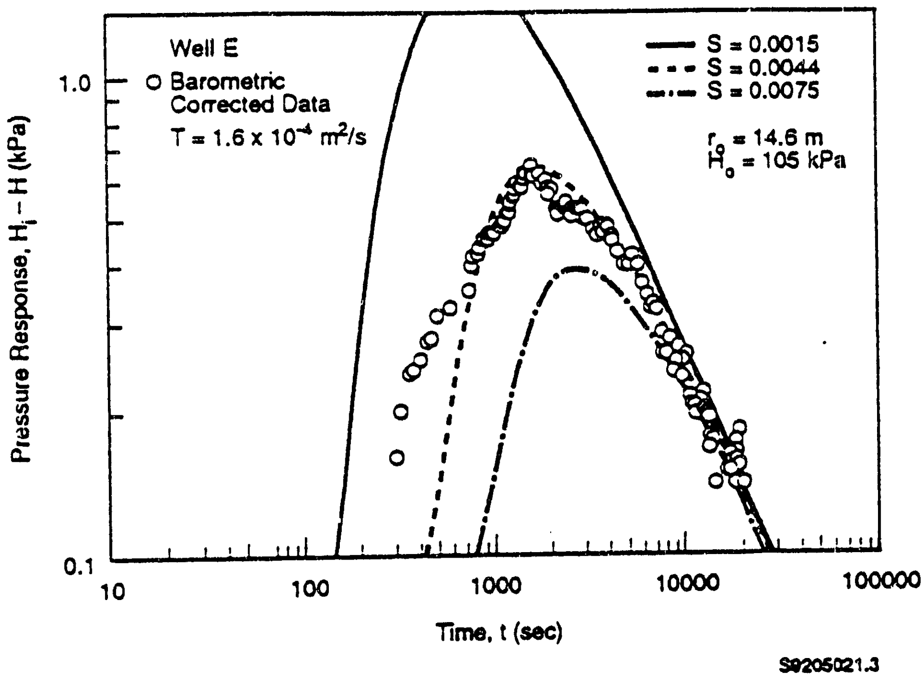

Figure 7 - Slug interference response at well E and effect of varying storativity.

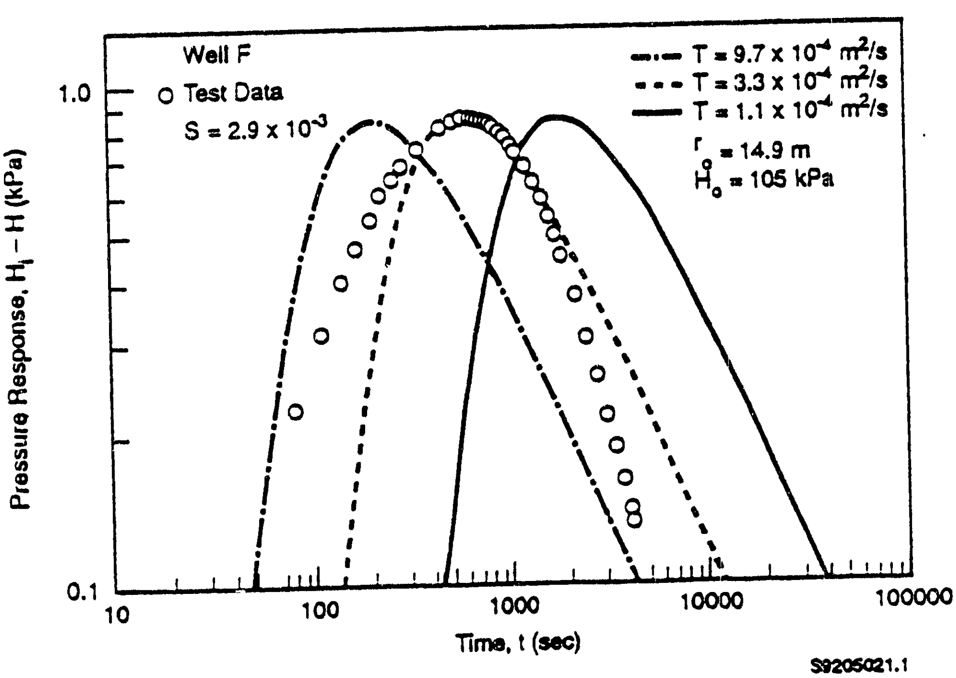

Figure 8 - Slug interference response at well F and effect of varying transmissivity

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