

MULTILEVEL NONLINEAR SLUG TESTS
TO CHARACTERIZE HIGH CONDUCTIVITY AQUIFERS

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**Multilevel Nonlinear Slug Tests
to Characterize High Conductivity Aquifers**

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Abstract

Multilevel Nonlinear Slug Tests to Characterize High Conductivity Aquifers

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Introduction

A considerable body of research has shown that the major control on the transport and fate of a pollutant as it moves through an aquifer is the spatial distribution of hydraulic conductivity. A number of theories have been developed to quantify in a generic sense the influence of these variations using stochastic processes or fractal representations. It is becoming increasingly apparent, however, that site-specific features of the hydraulic conductivity distribution (such as high conductivity zones) need to be quantified in order to reliably predict contaminant movement and design a remediation plan.

Nonlinear Slug-Test Model

While doing slug tests in high permeability aquifers, we have consistently seen deviations from the expected response of linear theoretical models, which have a systematic lack of fit and indicate that hydraulic conductivity varies with the initial displacement. We have developed a general nonlinear model based on the Navier-Stokes equation, nonlinear frictional loss, non-Darcian flow, acceleration effects, radius changes in the wellbore, and a Hvorslev model for the aquifer, which produces a very good fit to the field data (C.D. McElwee and M.A. Zenner, *Water Resources Research*, pp. 55-66, Jan. 1998).

We find that the proposed nonlinear model performs quite well, while reducing to traditional linear models (linear oscillatory, Hvorslev, etc.) when appropriate. The nonlinear model has three parameters: β which is related to radius changes in the water column, A which is related to the nonlinear head losses, and K the hydraulic conductivity. We find that the model is quite robust in its estimates of K over varying conditions and allows a wide range of slug test data to be analyzed with a greater accuracy than traditional linear methods.

Field Site and Results

We have a field site (GEMS - Geohydrologic Experimental and Monitoring Site) in the Kansas River alluvium (coarse sand and gravel overlain by silt and clay) that exhibits very high conductivities and nonlinear behavior for slug tests in the sand and gravel region. We know from extensive drilling, sampling, and a tracer test that the hydraulic conductivity varies considerably spatially. We have a large number of wells (about 70) completed at various depths (piezometer nests) and at various distances from each other. Many of the wells have a small screen at the bottom for testing a certain interval; however, at least 8 are fully screened throughout the sand and gravel interval. The slug tests are performed using an inflatable packer with a piston for slug test initiation, allowing accurate determination of the initial head and starting time for the slug test.

One multilevel well nest (nest 0) at GEMS has been extensively studied. Well 0-2 is at a depth of 46 feet and exhibits a K of .0022 ft/sec. Well 0-7 is completed at about 55 feet and indicates a K of .0056 ft/sec. Finally, well 0-5 ends at about 65 feet and appears to have a K of .0017. These data indicate that the most conductive zone is not at the base of the alluvium but is around 55 feet below the surface. This is in qualitative agreement with a tracer test that was run at the GEMS site within about 100 feet of nest 0. Data taken three years apart at well 0-7, with considerable differences in static water level, show quite different decay behaviors because of the different water column lengths; however, the nonlinear model was able to predict this behavior very well and yield almost identical values for K. At nest 0 an additional four inch well, 0-9 (completed at about 57 feet, nearly the same as well 0-7), was tested and gave a K value of .0054 ft/sec, very consistent with the value of .0056 ft/sec obtained from 0-7.

Some work has also been done at another well nest (nest 00) at GEMS. Well 00-1 is completed at a depth of about 56 feet and exhibits the highest hydraulic conductivity (.010 ft/sec) measured at GEMS to date. This agrees with the depth of the maximum hydraulic conductivity measured at nest 0, and is in qualitative agreement with the nearby tracer test.

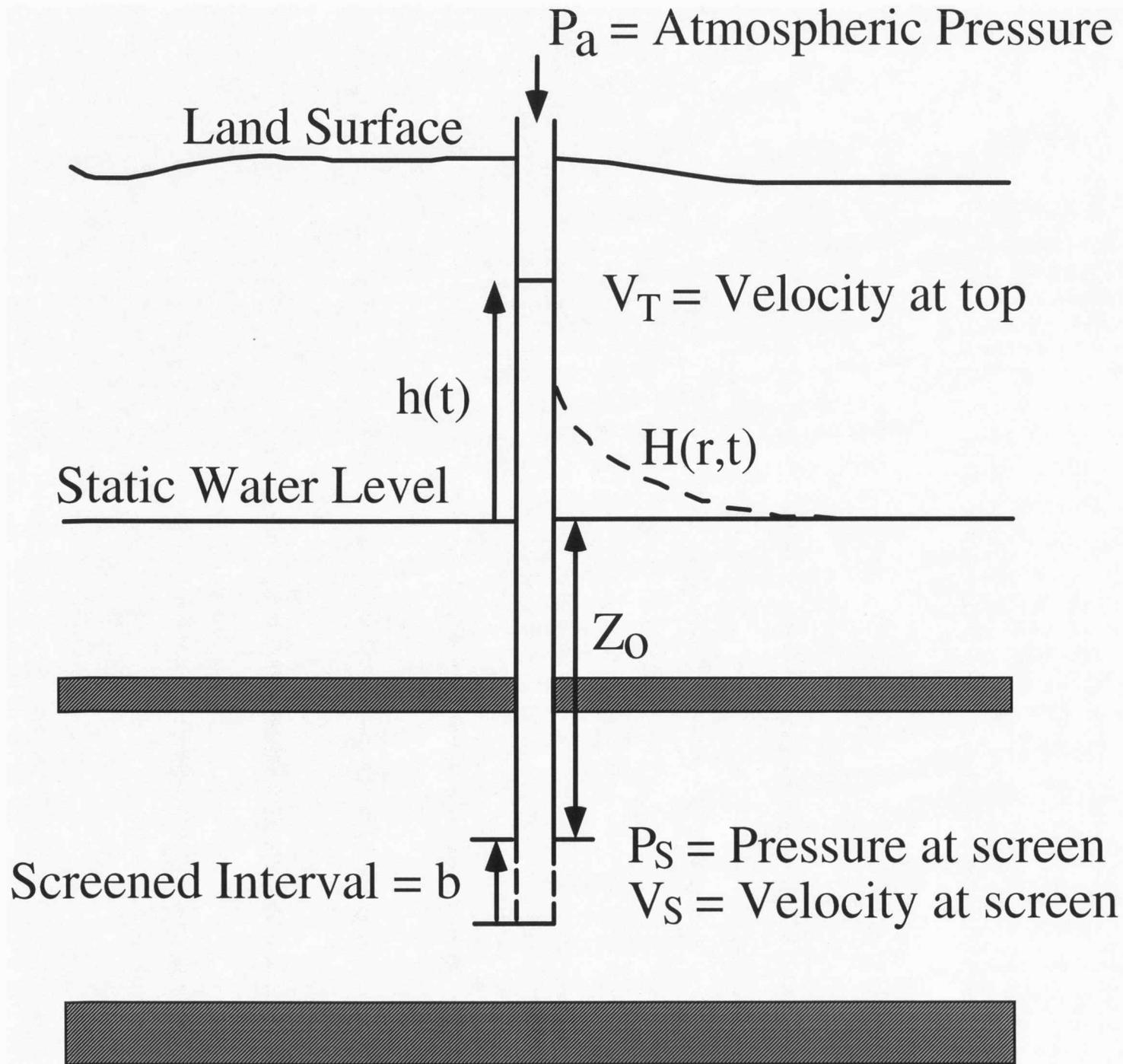
This summer extensive slug tests will be run at various well nests and single wells to map the hydraulic conductivity distribution at GEMS, both vertically and laterally. The nonlinear slug test model will be used to analyze the data. This new data will be presented along with the data mentioned above to illustrate the capabilities of the nonlinear model for high conductivity aquifers.

Introduction

- The control and remediation of contamination is a high priority
- Hydraulic conductivity (K) is a critical parameter
- Slug tests are widely used to determine K
- Slug test technology has been abused
- Need for improved techniques

Typical Slug Test Arrangement

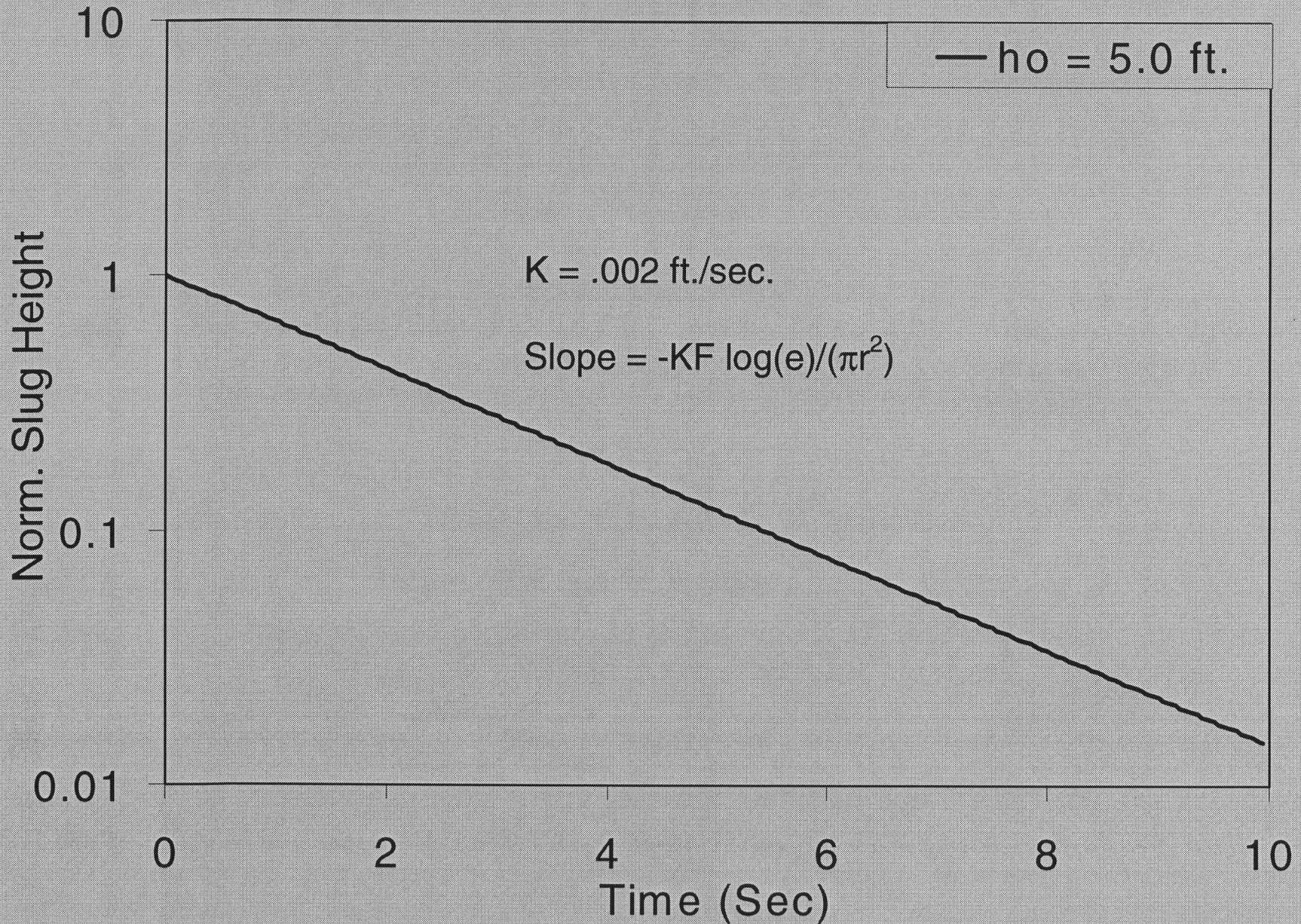
- The next slide shows a typical slug test arrangement
- $h(t)$ is the head in the well at any time above the static value
- Z_0 is the length of water below the static level to the top of the screen
- b is the length of the screen



Linear Slug Test Models

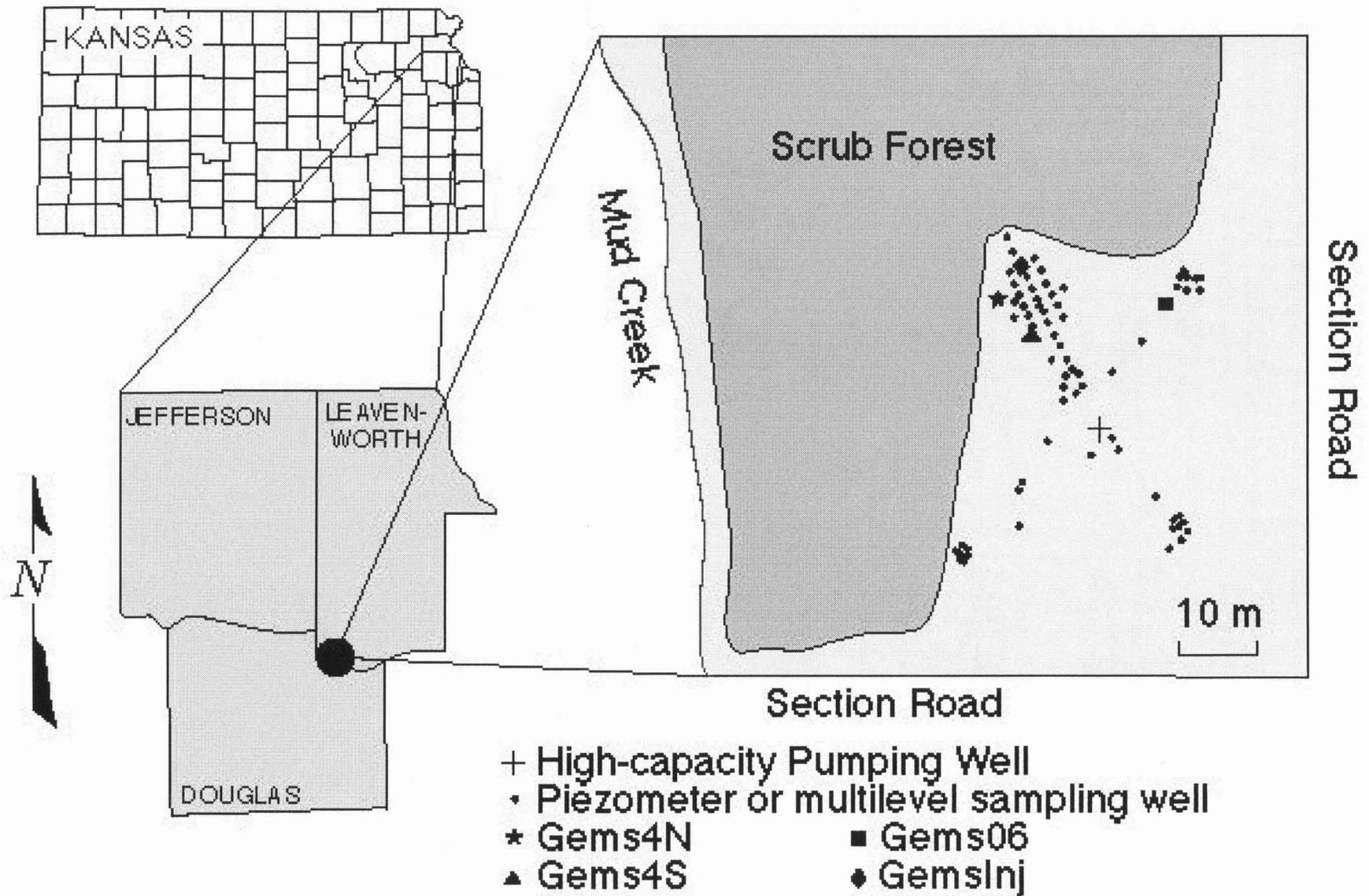
- Linear models predict a straight line on a log-linear plot
- The slope of the line is proportional to K
- Normalized plots should look the same for all initial heads
- An example plot is shown in the next slide

Typical Hvorslev Response



GEMS

- We have developed a Geohydrological Experiment and Monitoring Site (GEMS)
- Located in Kansas River Alluvium
- Coarse sand and gravel overlain by silt and clay
- Highly permeable
- Slug tests only last a few seconds

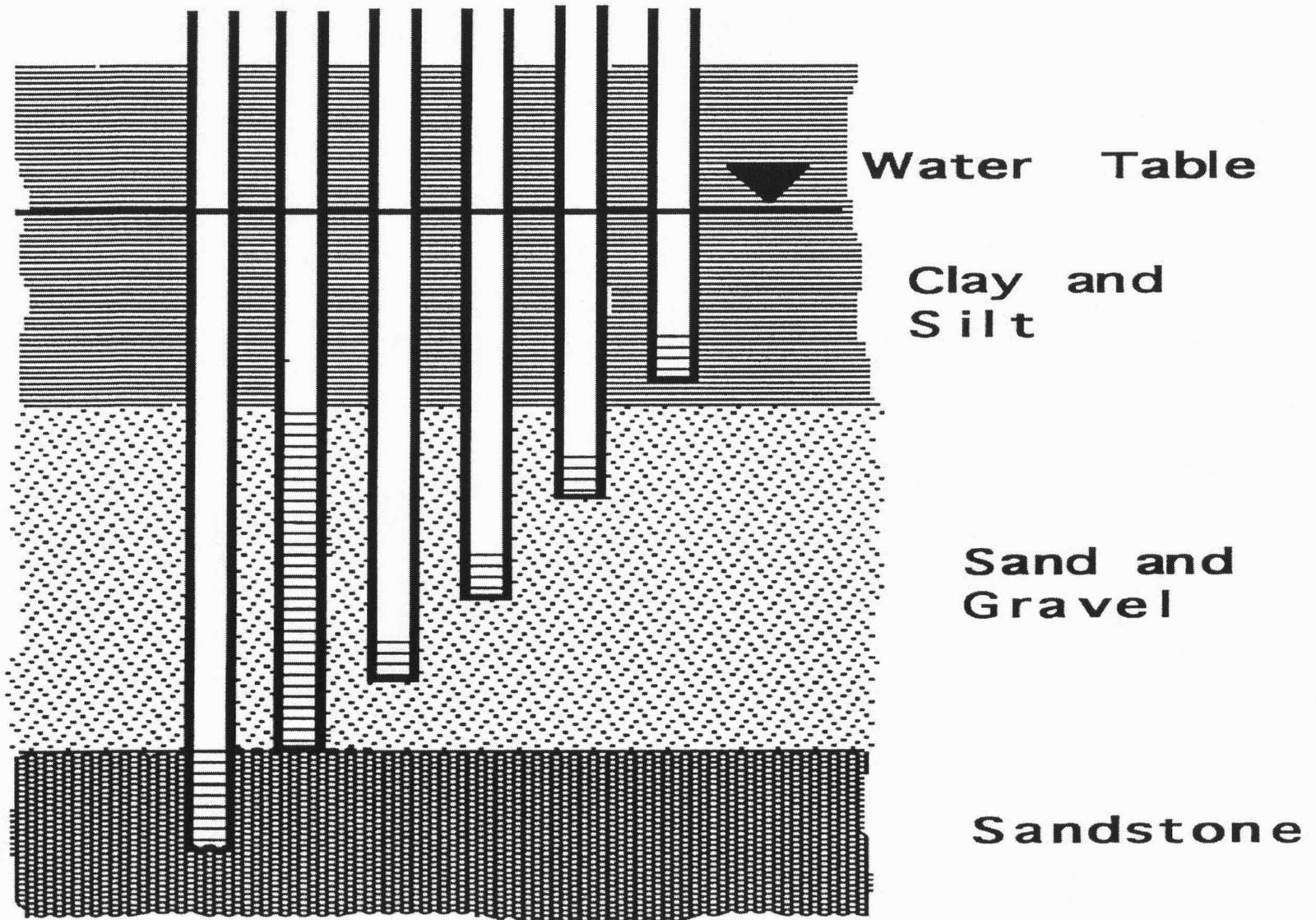


Location map for the Geohydrologic Experimental and Monitoring Site (GEMS).

Well Nests at GEMS

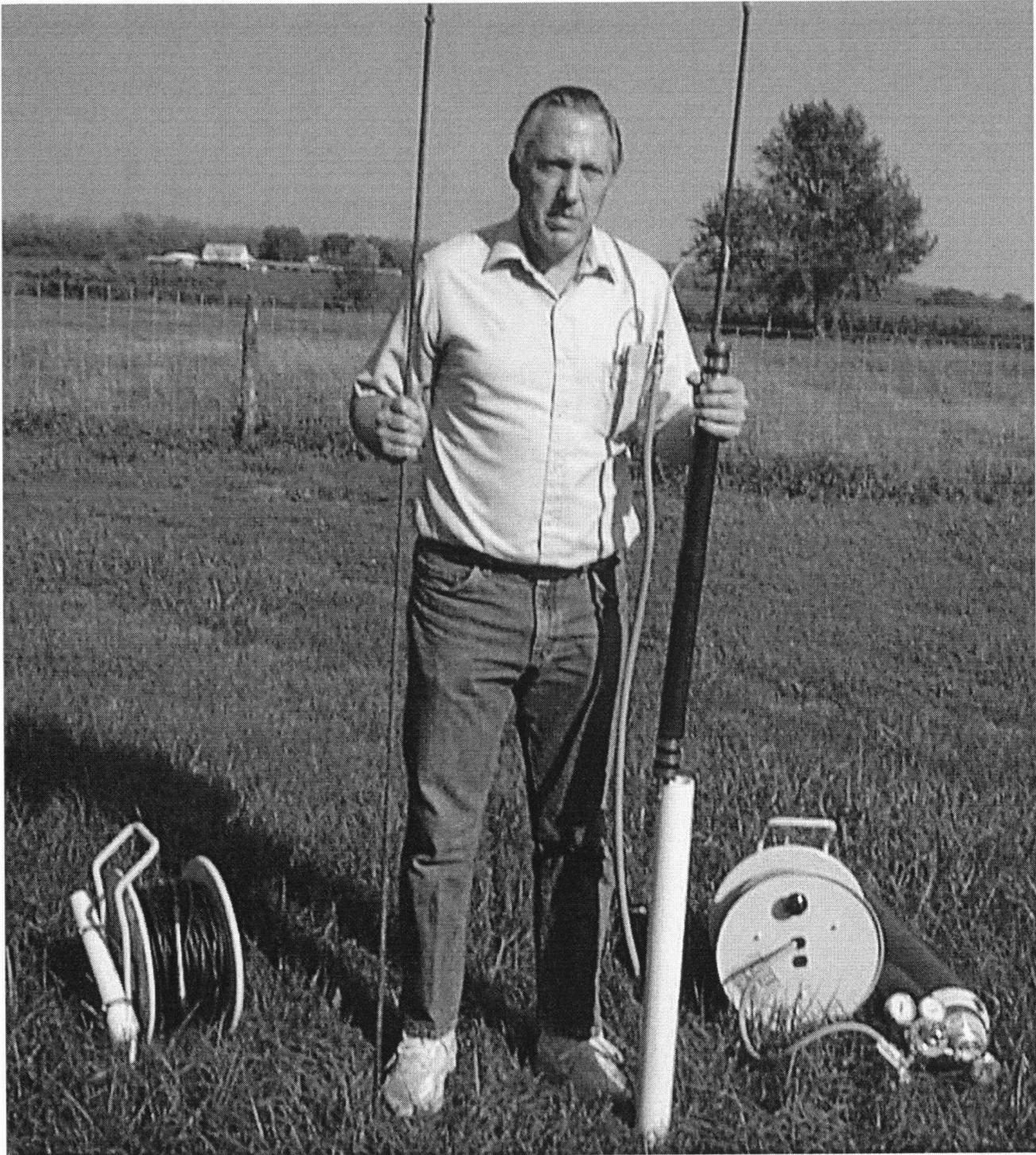
- A typical well nest is shown in the next slide. Typically there is a fully screened well and several wells with short screens completed at various depths. In some nests we may have a well completed into the bedrock.

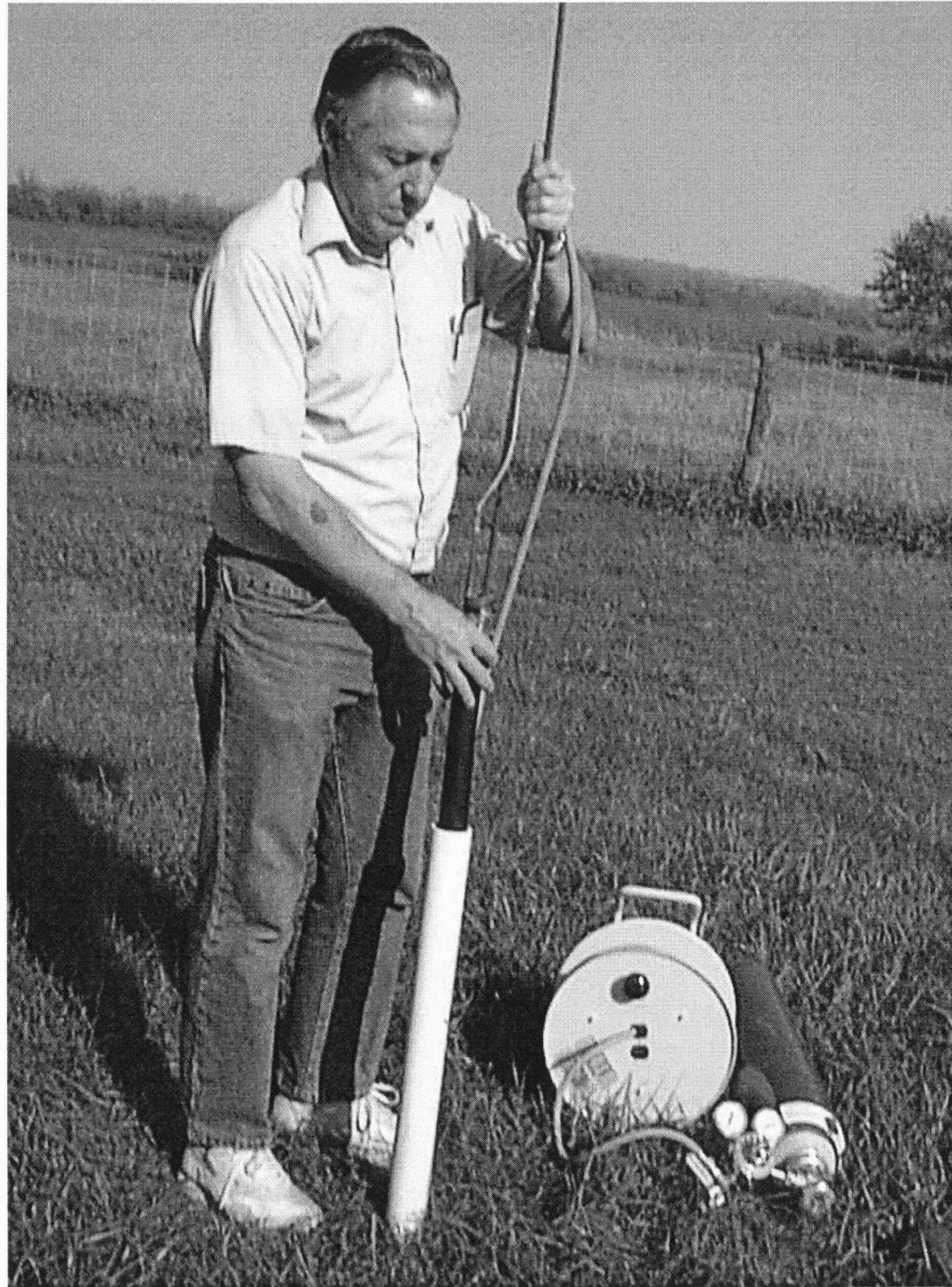
Typical GEMS Well Nest

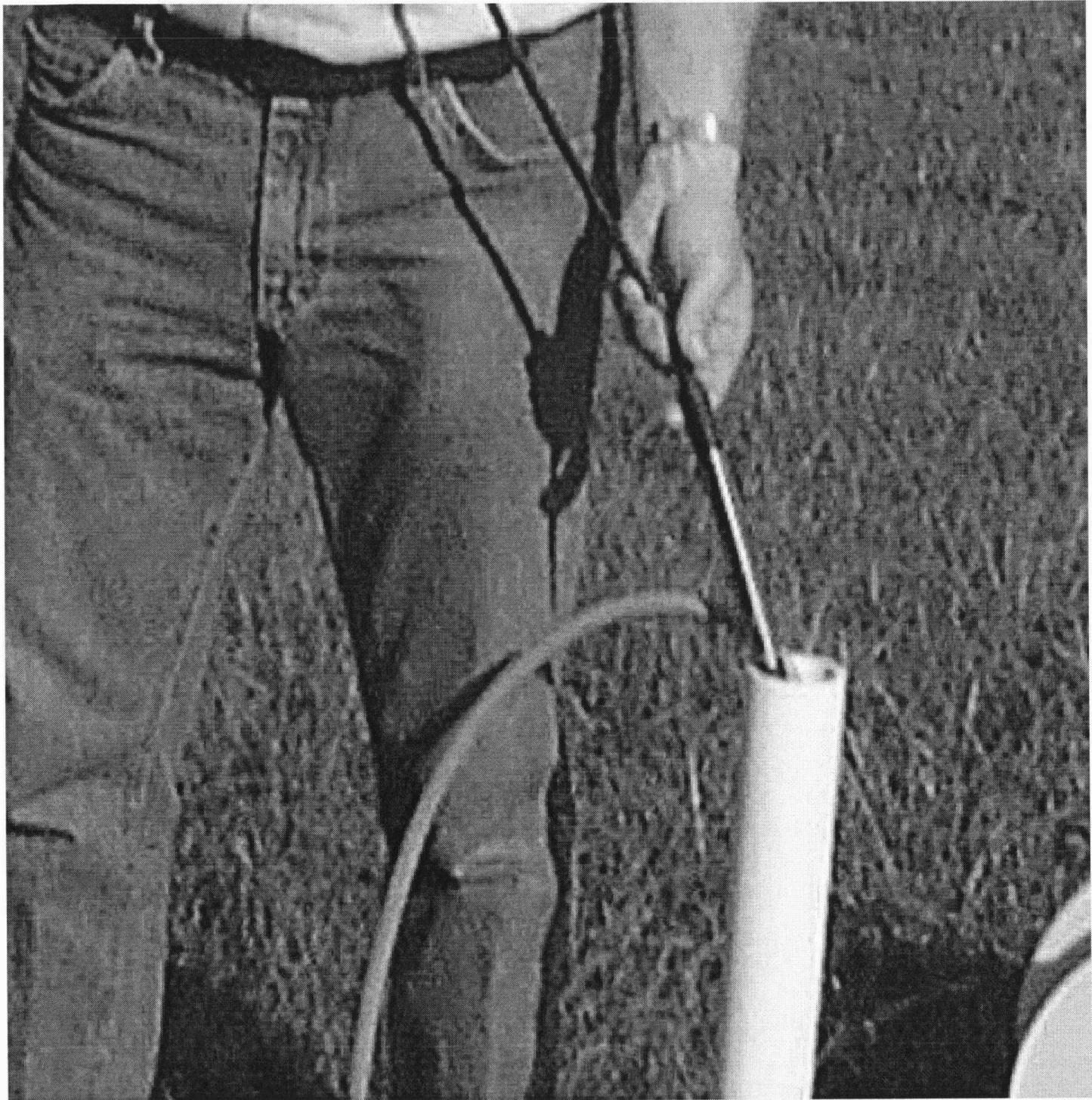


Slug-Test Equipment

- The next few slides will show the equipment typically used to perform slug tests at GEMS.
- The packer is placed with the help of pump rods.
- We inflate a packer with compressed nitrogen some distance below the water table.
- A pressure transducer is placed above the packer

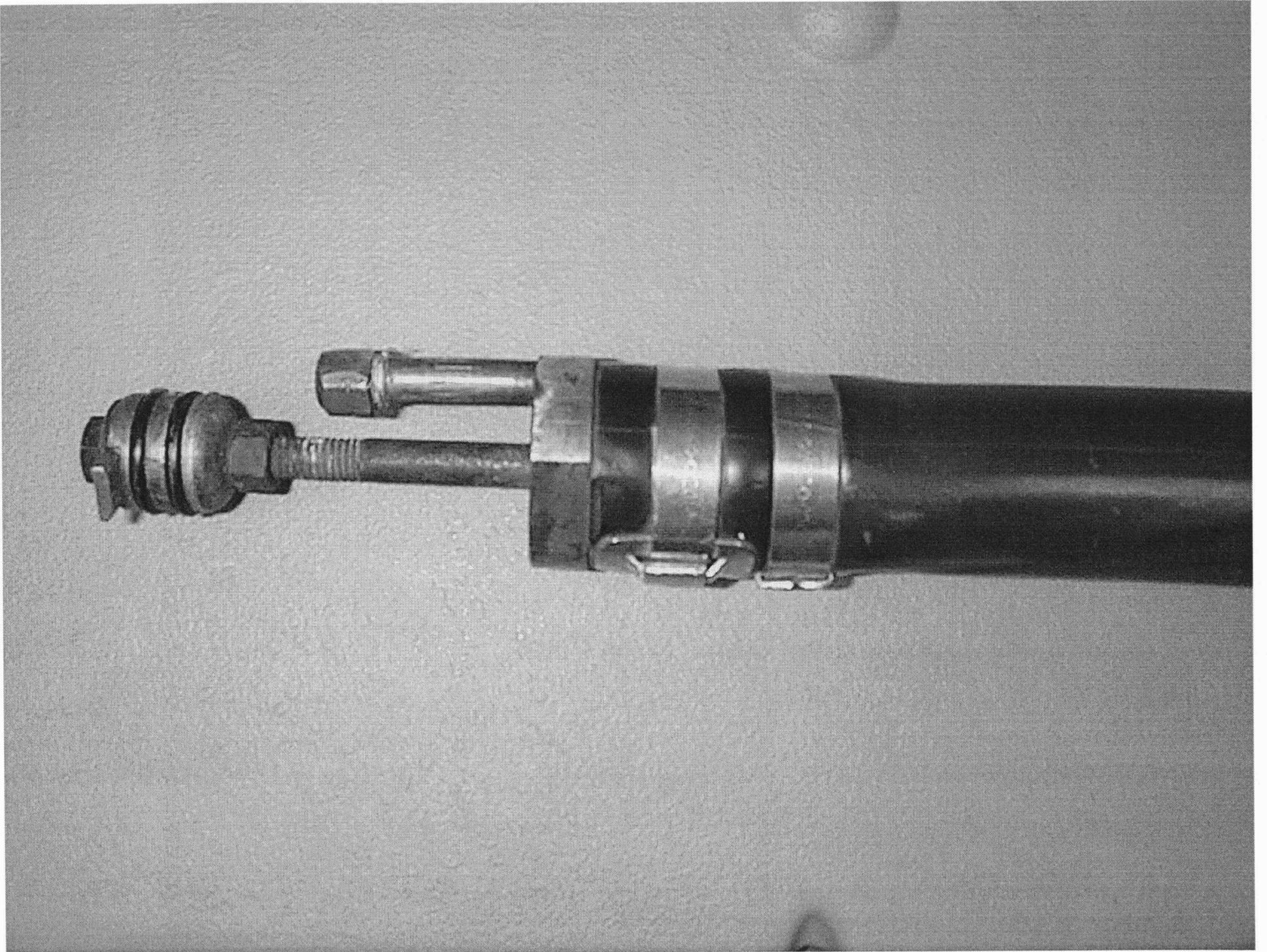


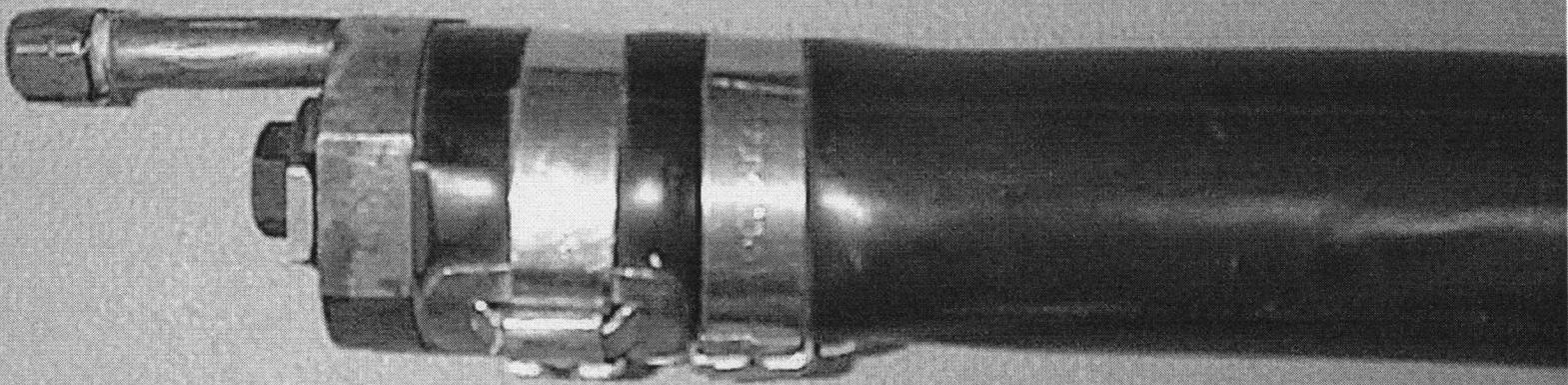




Instigation of Slug Test

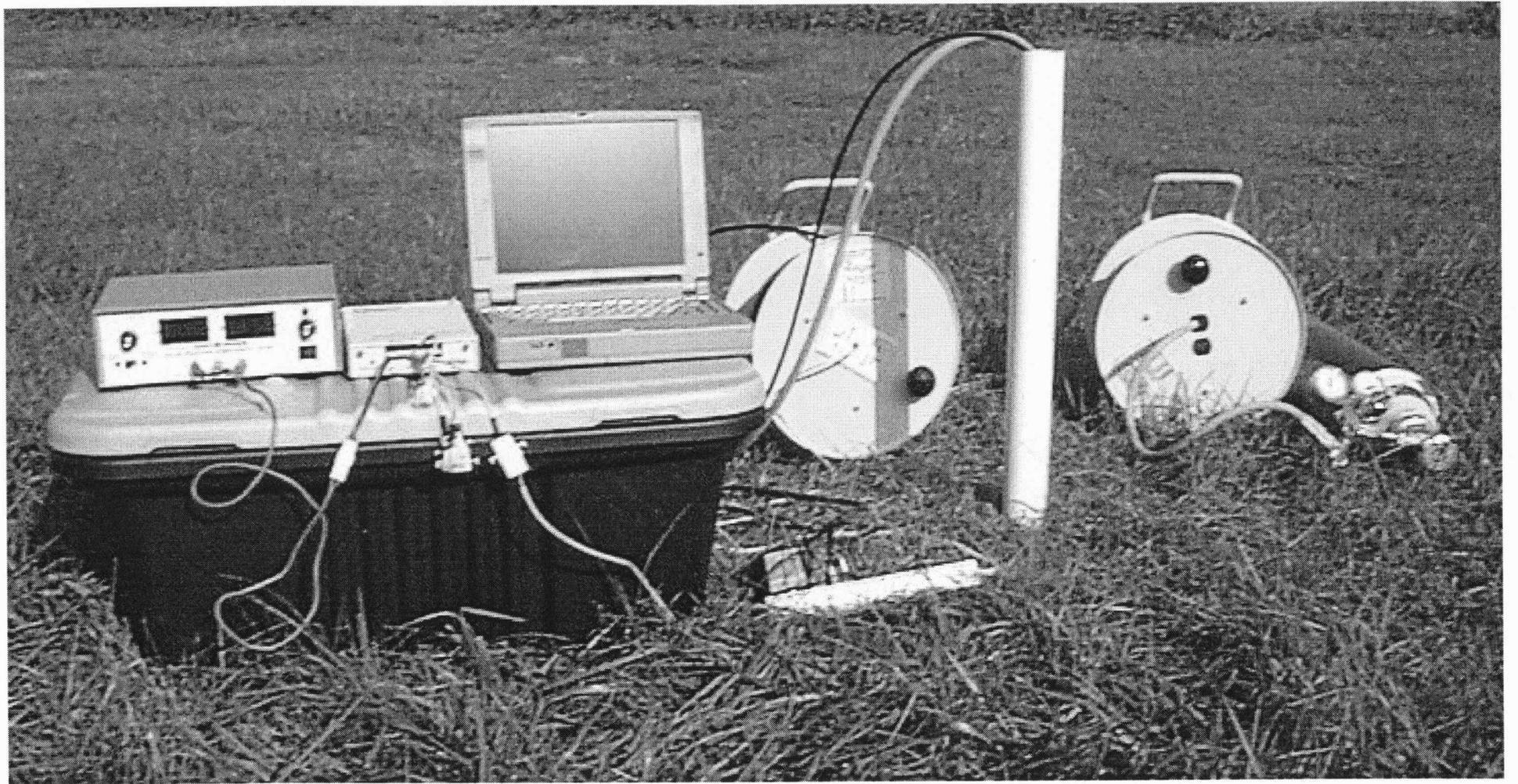
- There is a piston on the end of the pump rods.
- The pump rods may be moved to open and close throat of the packer.
- The packer is closed and water is added.
- When the piston is lowered the slug test is instigated.





Recording of Slug-Test Data

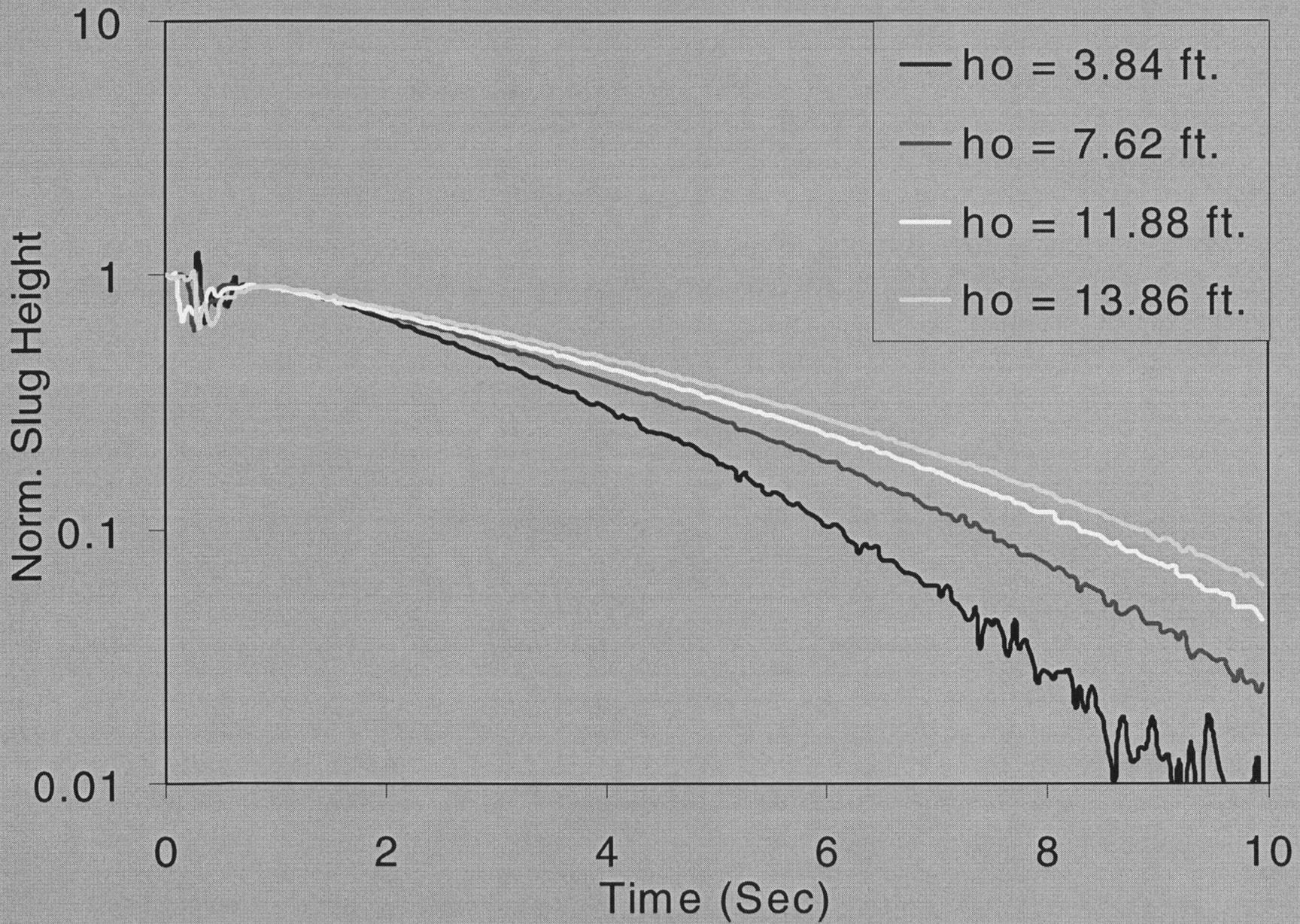
- The slug tests are over very quickly.
- It is necessary to use a high quality data logger with high accuracy and fast sample rate.
- Our data logger has 16 bit accuracy
- We used a 20 Hz sample rate.



Slug Tests at GEMS

- We see deviations from the traditional linear models
- No straight line plot
- The curves are concave downward or oscillatory
- Dramatic dependence on initial head

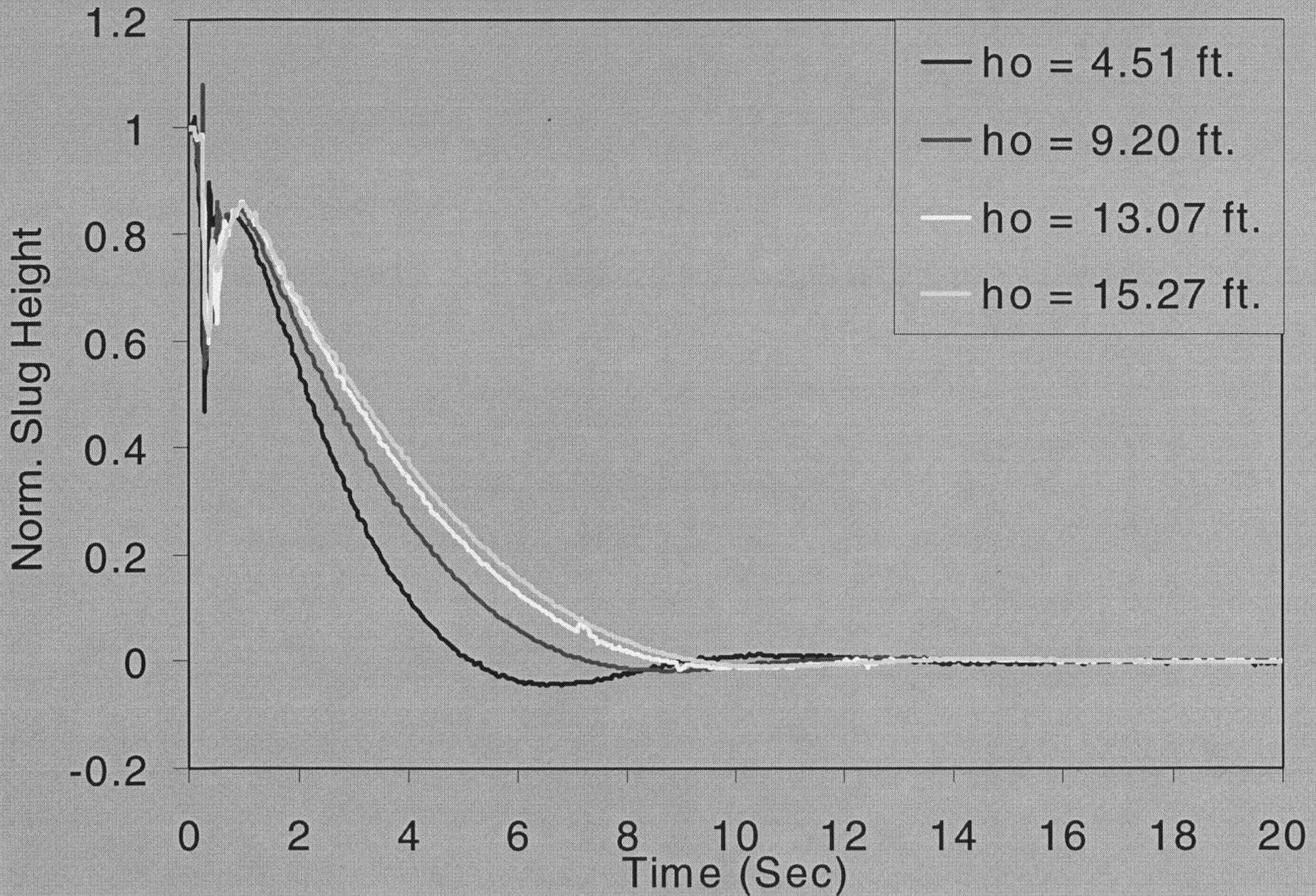
Slug Test Response at GEMS Well 0-2



Typical Oscillatory Behavior at GEMS

- Some wells have an oscillatory response
- The response depends on initial head
- Linear models are unable to describe these data

Slug Test Response at GEMS Well 0-7



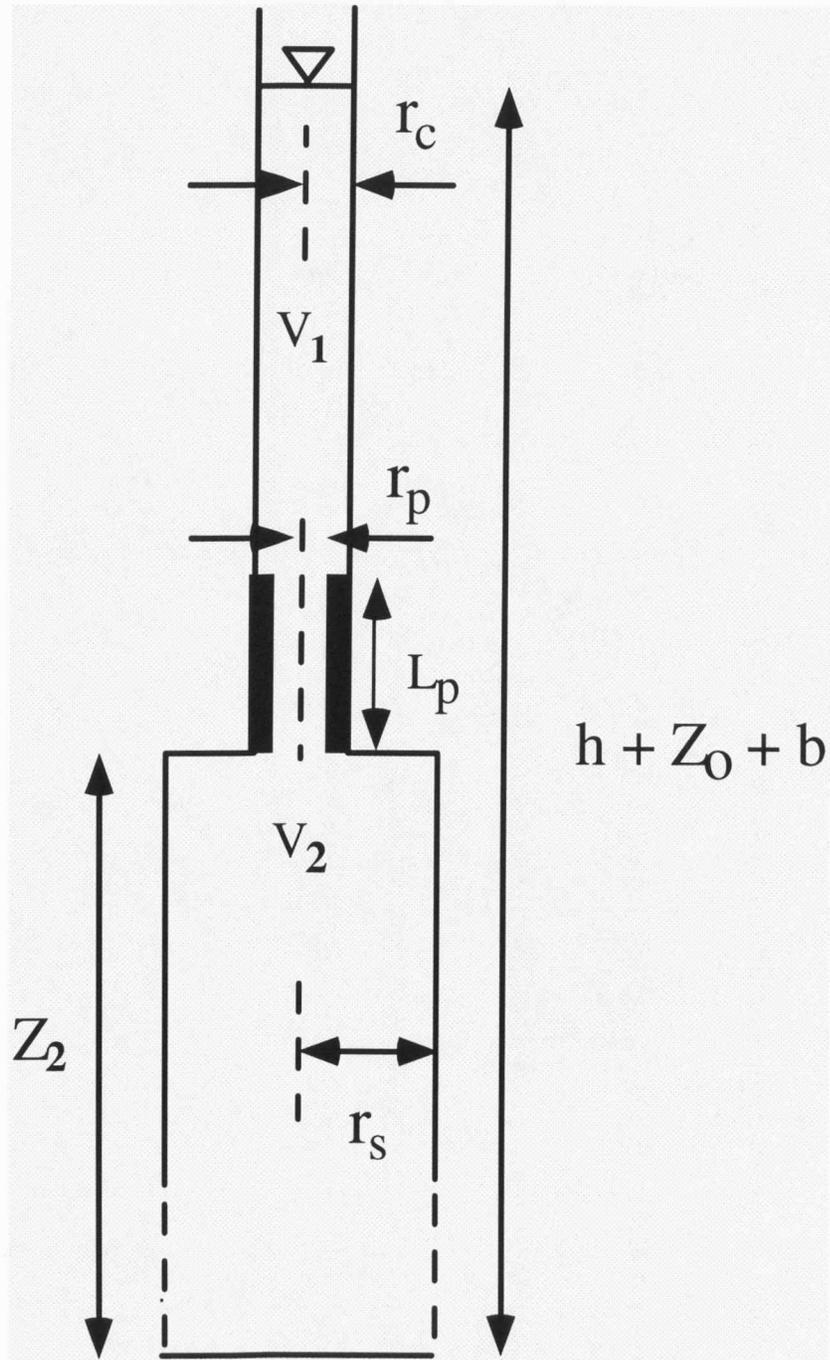
The General Nonlinear Model

$$(h + z_o + b + \beta) \frac{d^2 h}{dt^2} + A \left| \frac{dh}{dt} \right| \frac{dh}{dt} + \frac{g \pi r_c^2}{FK} \left(\frac{dh}{dt} \right) + gh = 0$$

- Acceleration effects in wellbore and aquifer
- Nonlinear frictional loss
- Non-Darcian flow
- Radius changes in the wellbore
- Hvorslev model for aquifer

Typical Wellbore for Slug Tests

- Radius change due to packer
- Radius change due to casing diameter change

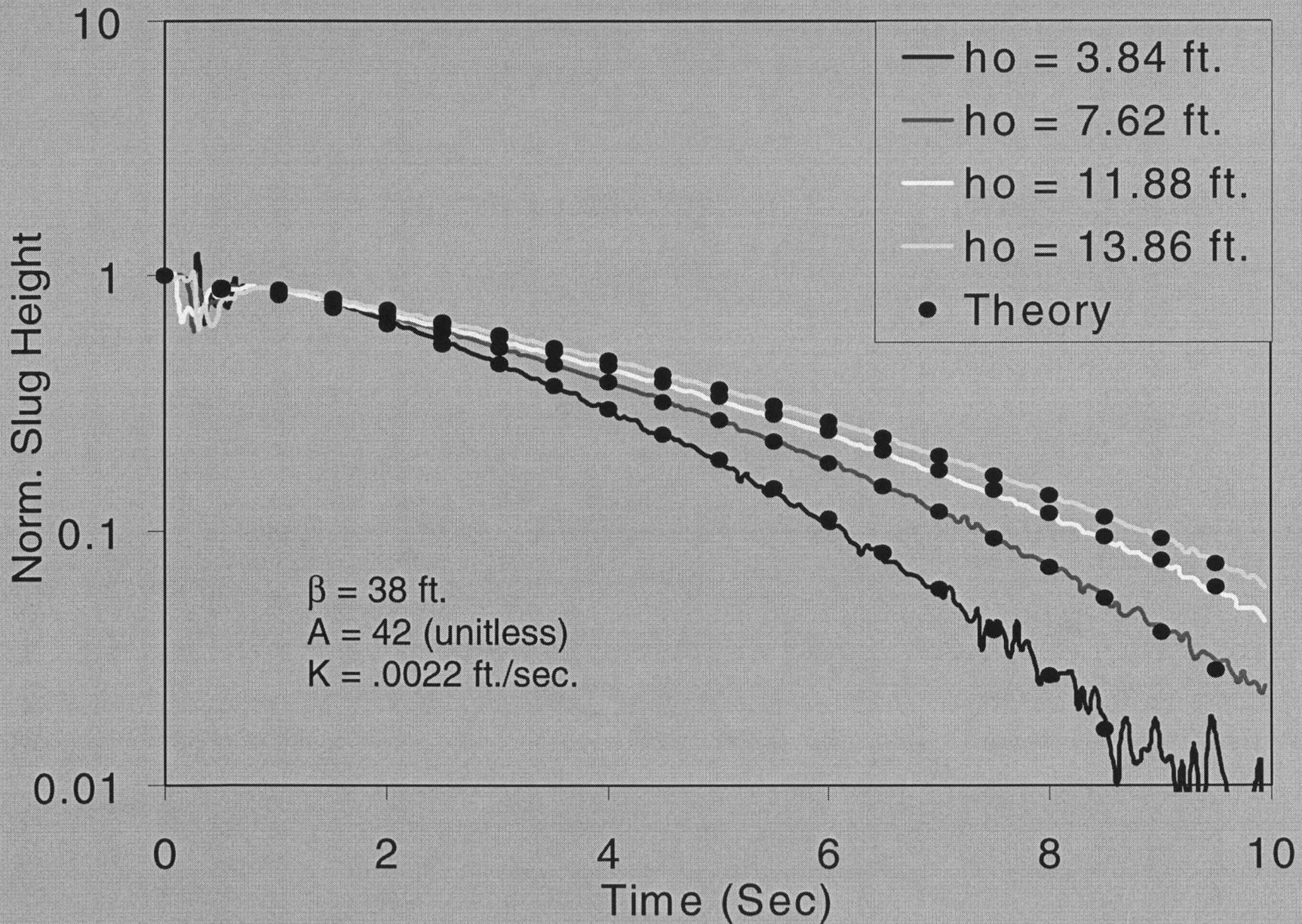


Typical Slug-Test Wellbore with Packer

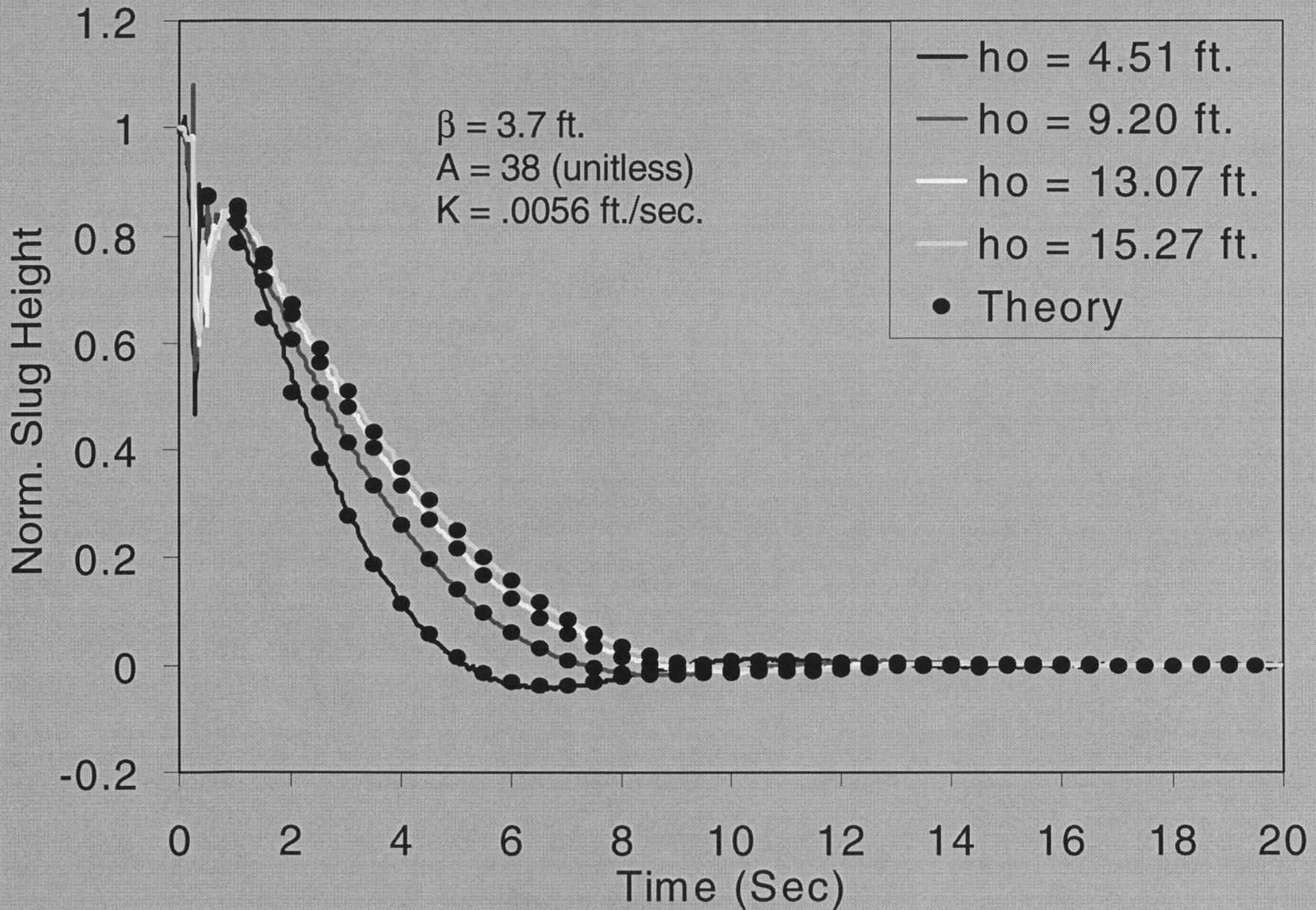
Fit of Nonlinear Model to Data

- The nonlinear model has three parameters (β , A , K) which may be adjusted to fit data
- The theoretical values are shown as dots
- Both non-oscillatory and oscillatory data are explained very well
- A single set of parameters describes all head data

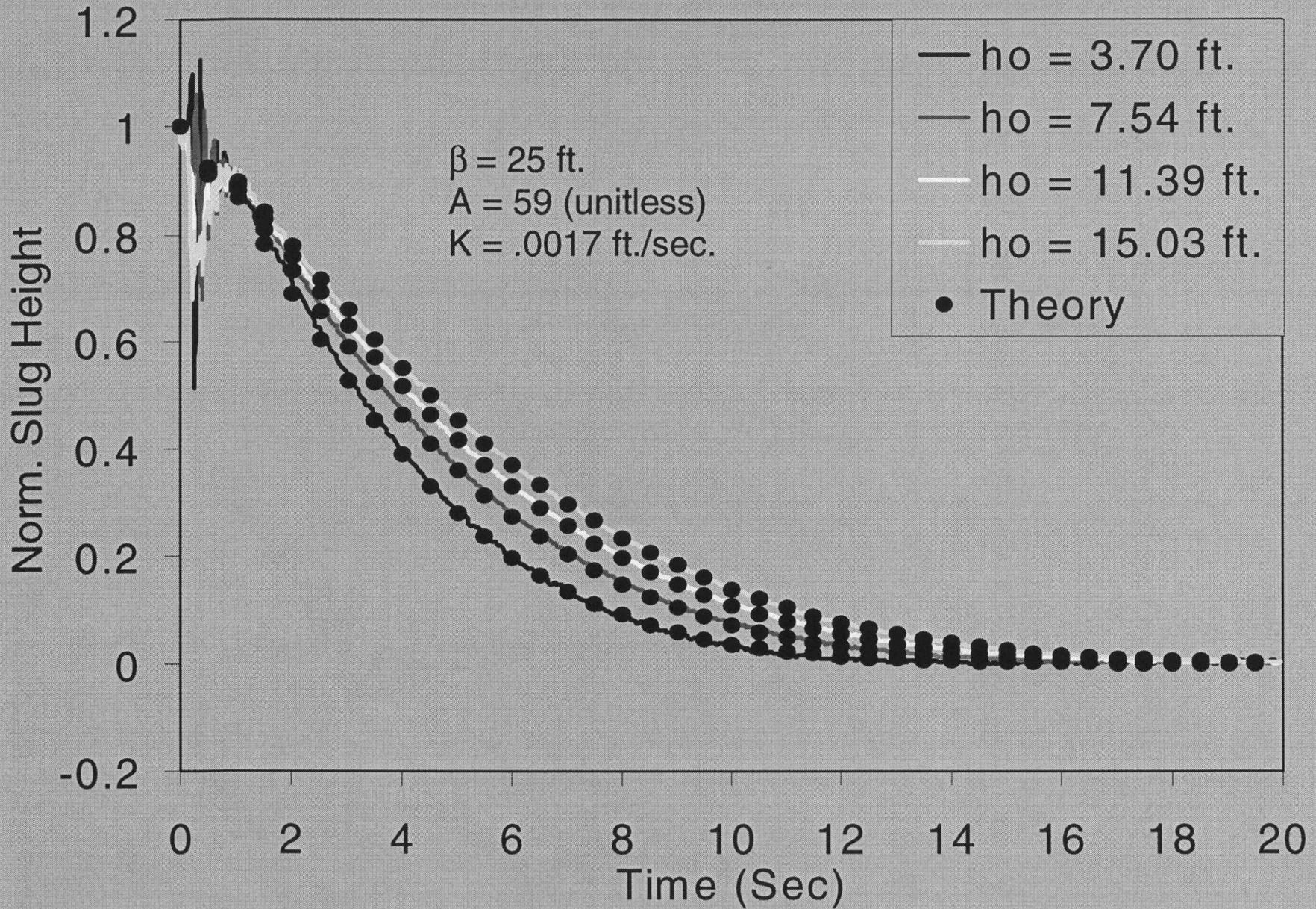
Slug Test Response at GEMS Well 0-2



Slug Test Response at GEMS Well 0-7



Slug Test Response at GEMS Well 0-5

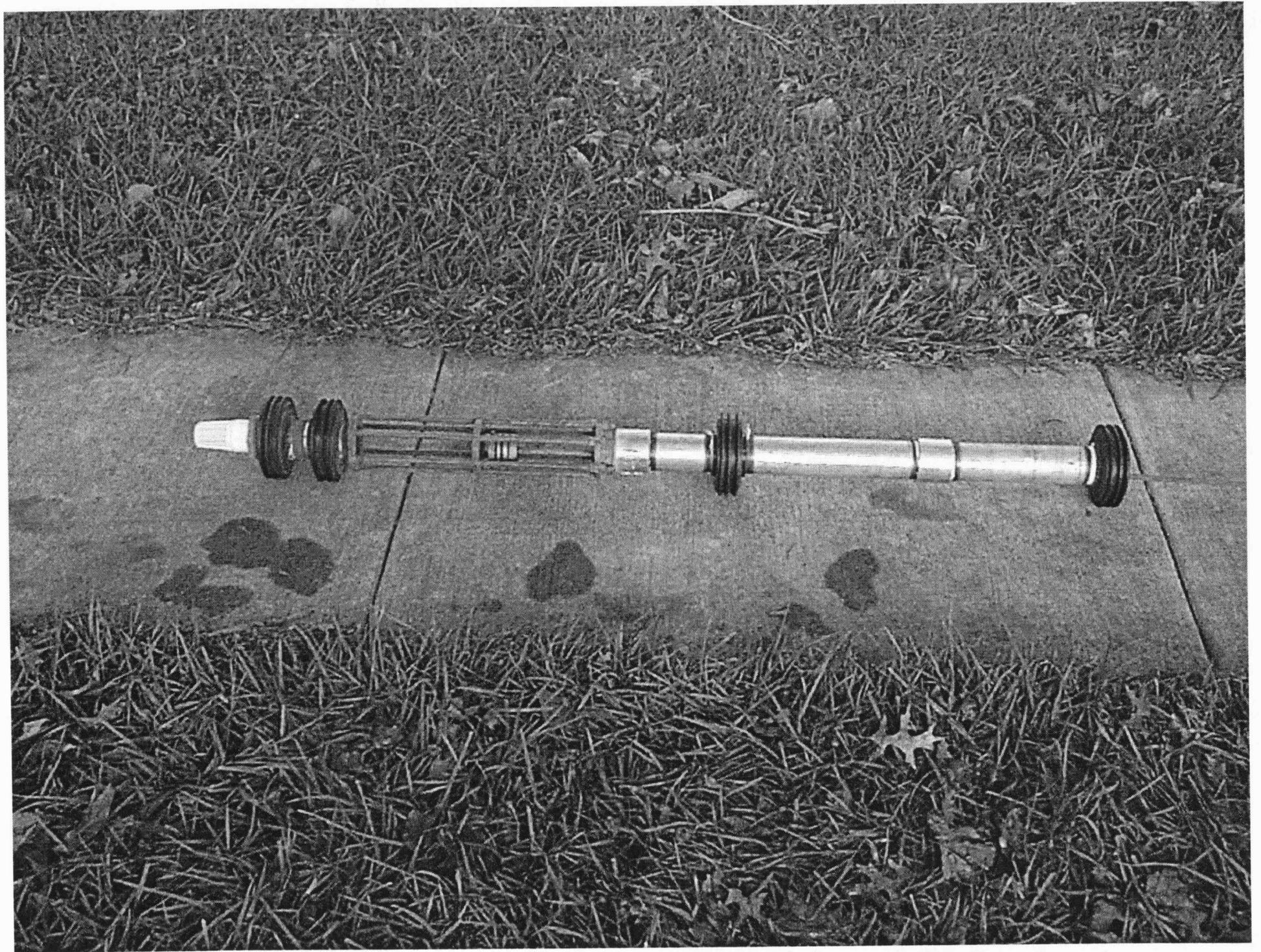


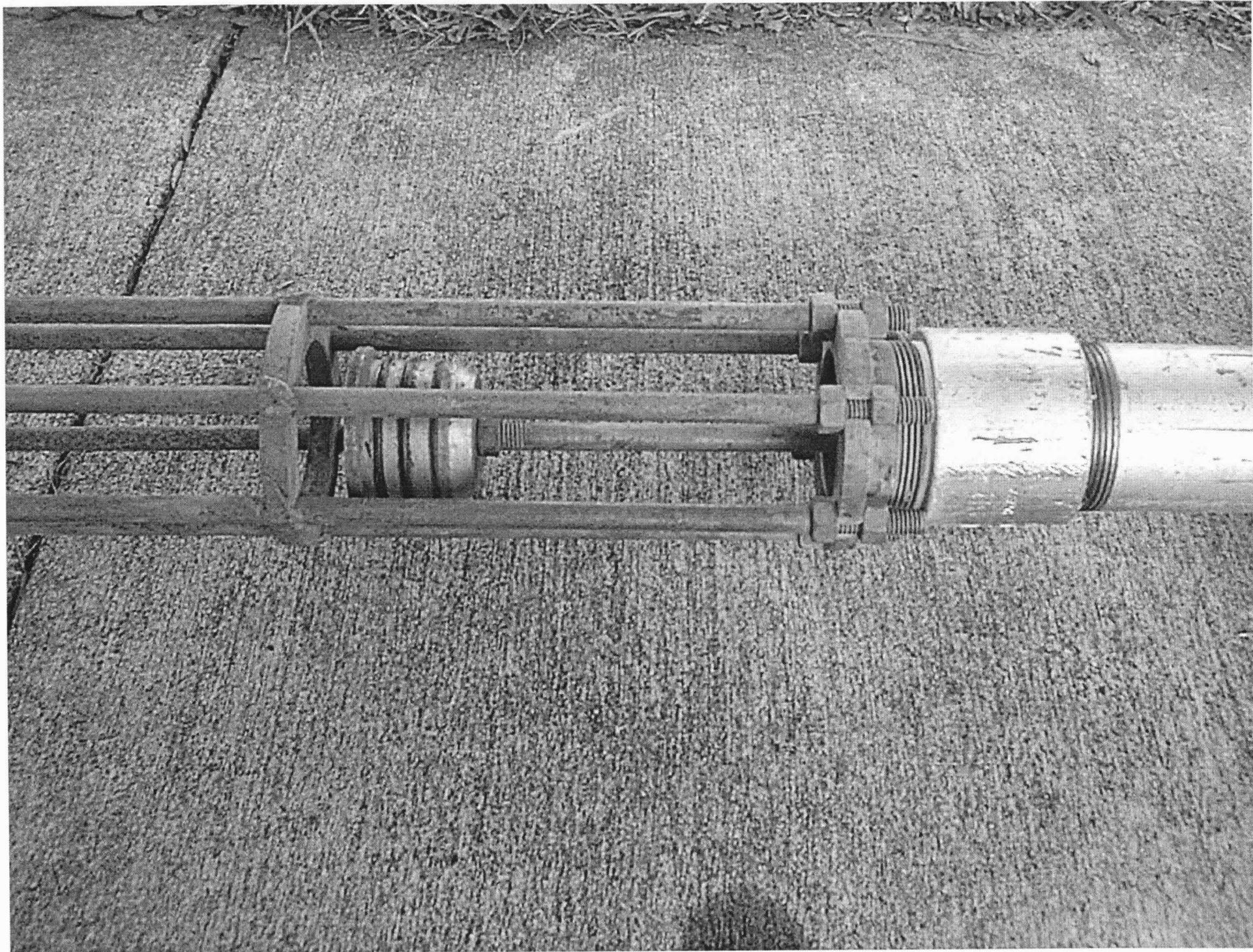
Measuring K Versus Depth

- Well 0-2, depth 46 ft., $K = .0022$ ft/sec
- Well 0-7, depth 55 ft., $K = .0056$ ft/sec
- Well 0-5, depth 65 ft., $K = .0017$ ft/sec
- Depths are below top of casing, BTOC
- This is in qualitative agreement with a tracer test

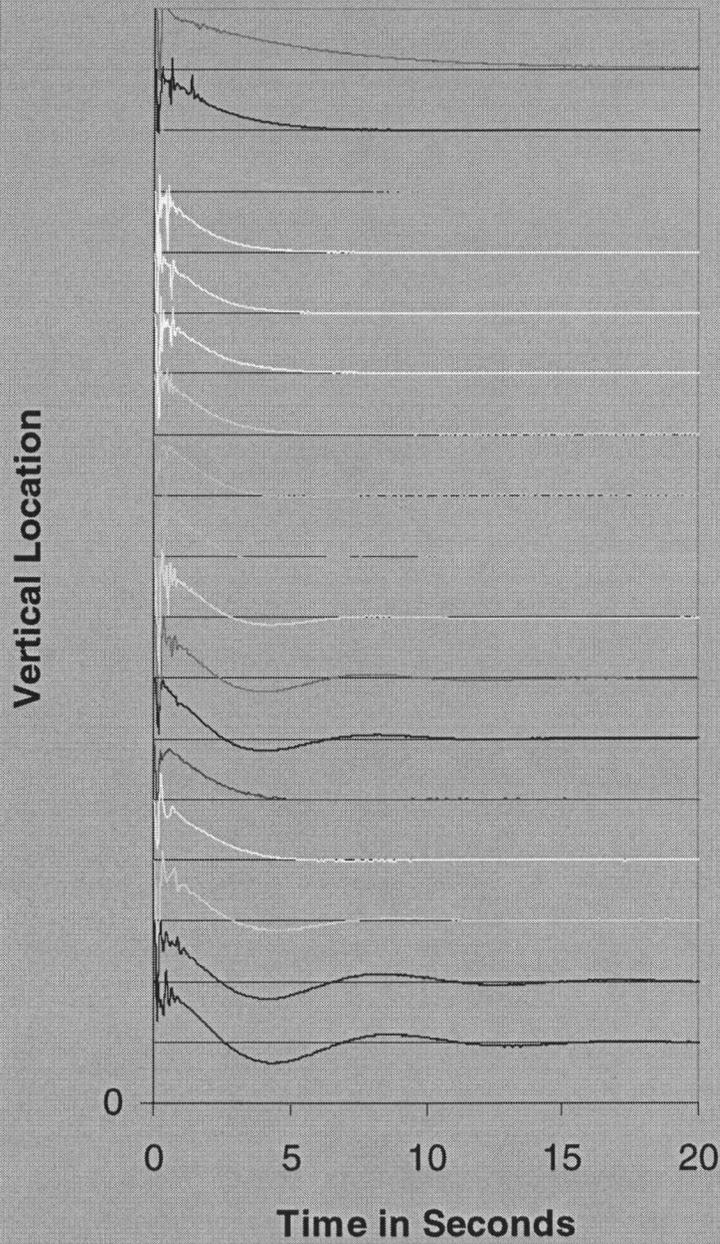
Multilevel Slug Tests

- The GEMS Injection Well was used.
- Casing radius is 5 inches in diameter.
- Packers used above and below a 2 foot slugged interval.
- Riser pipe is 2 inches in diameter.
- 17 locations in the sand and gravel section.
- The following 2 slides show the packer and piston assembly.





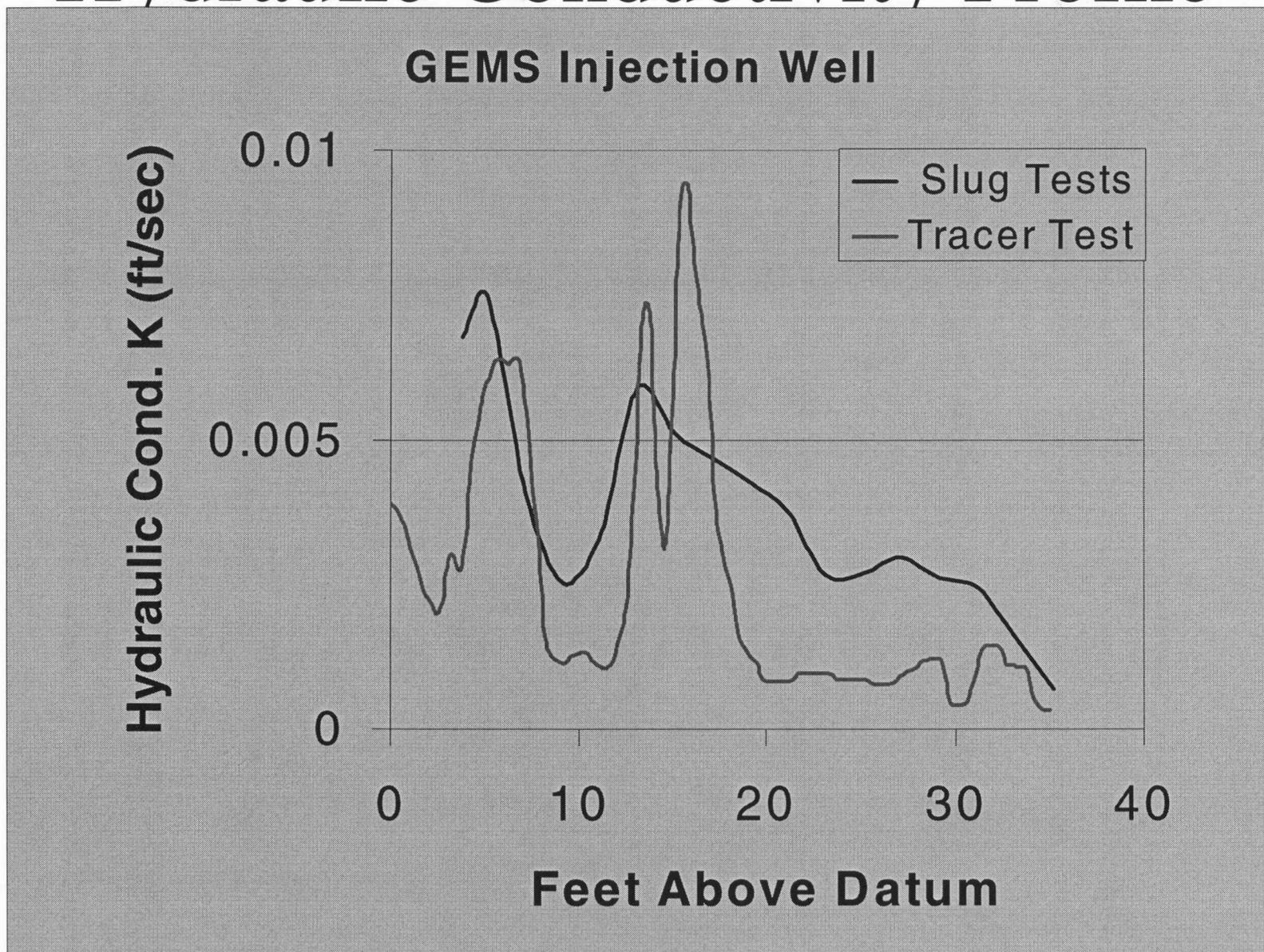
Slug-Test Response With Depth



Hydraulic Conductivity Profile

- The next 2 slides show the vertical hydraulic conductivity profile obtained for the GEMS injection well with the multilevel slug tests. Datum is approximately 70 feet below ground surface
- Also plotted is an inferred conductivity distribution for a bromide tracer test that was run earlier.
- The structure of two higher conductivity zones seems to be consistent.

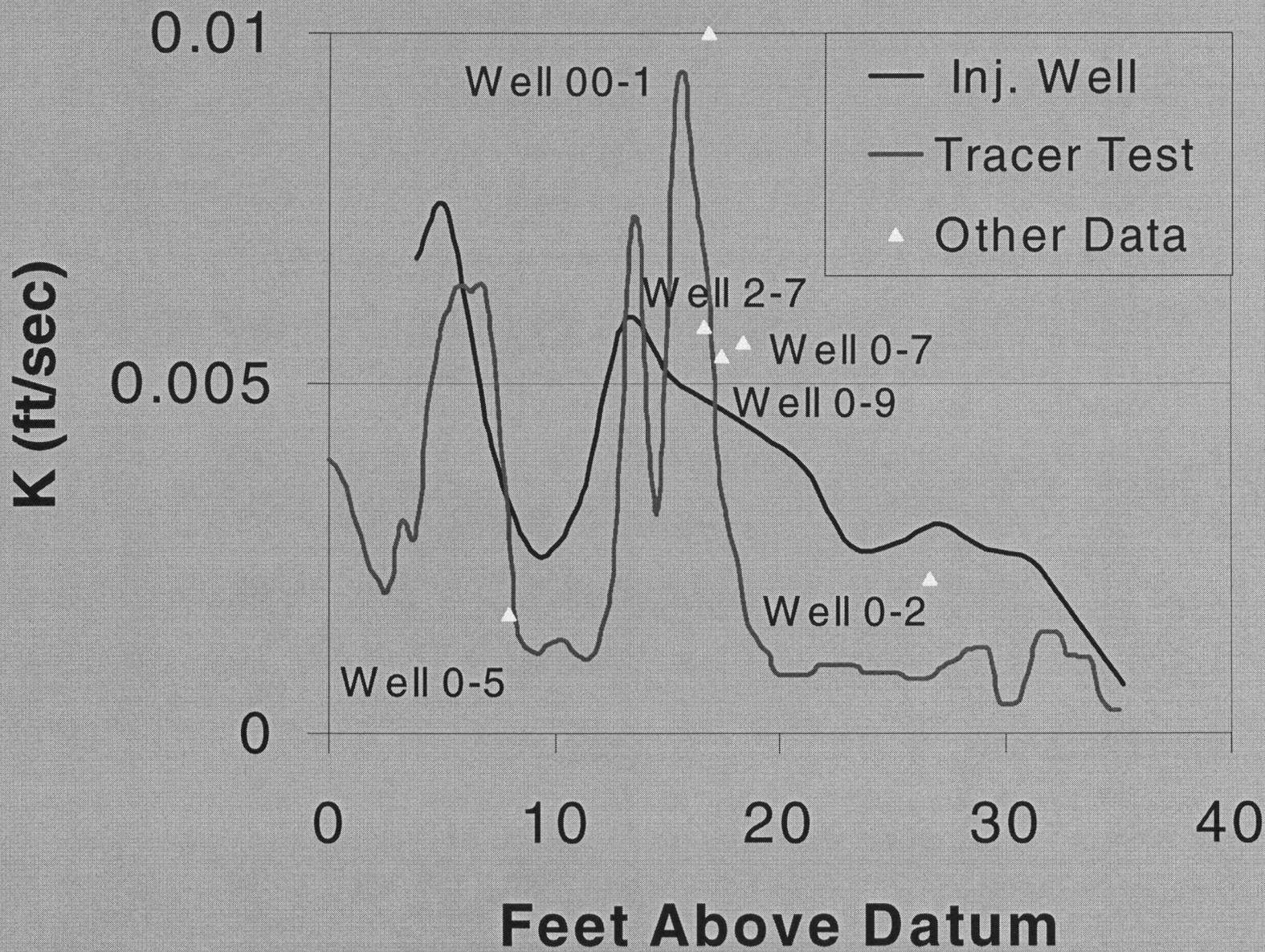
Hydraulic Conductivity Profile



Individual well data

- The next slide shows some additional individual well slug-test data plotted as triangles.
- This data seems to be consistent with the profiles obtained from slug tests and the bromide tracer test.

Hydraulic Conductivity Data



Additional Slug-Test Data

- 10 additional wells at various locations and depths have been tested.
- They have not been completely analyzed.
- Visually they seem to fit with the vertical K structure shown here.
- The goal is to produce a 3-D map of K over the GEMS site.

Summary and Conclusions

- Slug tests in high permeability aquifers can exhibit nonlinear behavior
- The nonlinear effects make the response dependent on initial head
- Inertial effects, radius variations, and nonlinear losses can be important for high permeability aquifers

Summary and Conclusions (Continued)

- This model reduces to conventional linear models when appropriate
- The model estimates for K are quite robust for a variety of physical situations in a given well
- This model allows a wide range of slug test data to be analyzed with greater accuracy

Reference

- McElwee, C.D., and Zenner, M., 1998, A nonlinear model for analysis of slug-test data: *Water Resources Research*, v. 34, no. 1, pp. 55-66.