KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 98-66

SLUG TESTS IN EXTREMELY PERMEABALE AQUIFERS

by

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Prepared for presentation at
The 43 Annual Midwest Ground Water Conference
Lawrence, Kansas
Oct. 14, 1998

KGS Open File Report #98-66

Abstract

Slug Tests in Extremely Permeable Aquifers

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One of the most popular techniques for measuring hydraulic conductivity is the slug test, due to the simplicity and cost effectiveness. We have a field site called GEMS (Geohydrologic Experimental and Monitoring Site), with about 70 wells, that is located in the Kansas River Alluvium. The site consists of about 70 feet of alluvium; 35 feet of silt and clay overlying 35 feet of a generally fining upward sequence of sand and gravel. While doing slug tests in some of the coarser material, we have observed that conventional linear theories do not explain the field data well, because they have a systematic lack of fit and indicate that hydraulic conductivity varies with the initial slug 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. We find that the proposed nonlinear model explains the field data quite well, while reducing to traditional linear models (linear oscillatory, Hvorslev, etc.) when appropriate. The nonlinear model has three parameters: ß which is related to radius changes in the water column, A which is related to the nonlinear head losses, and K the hydraulic conductivity.

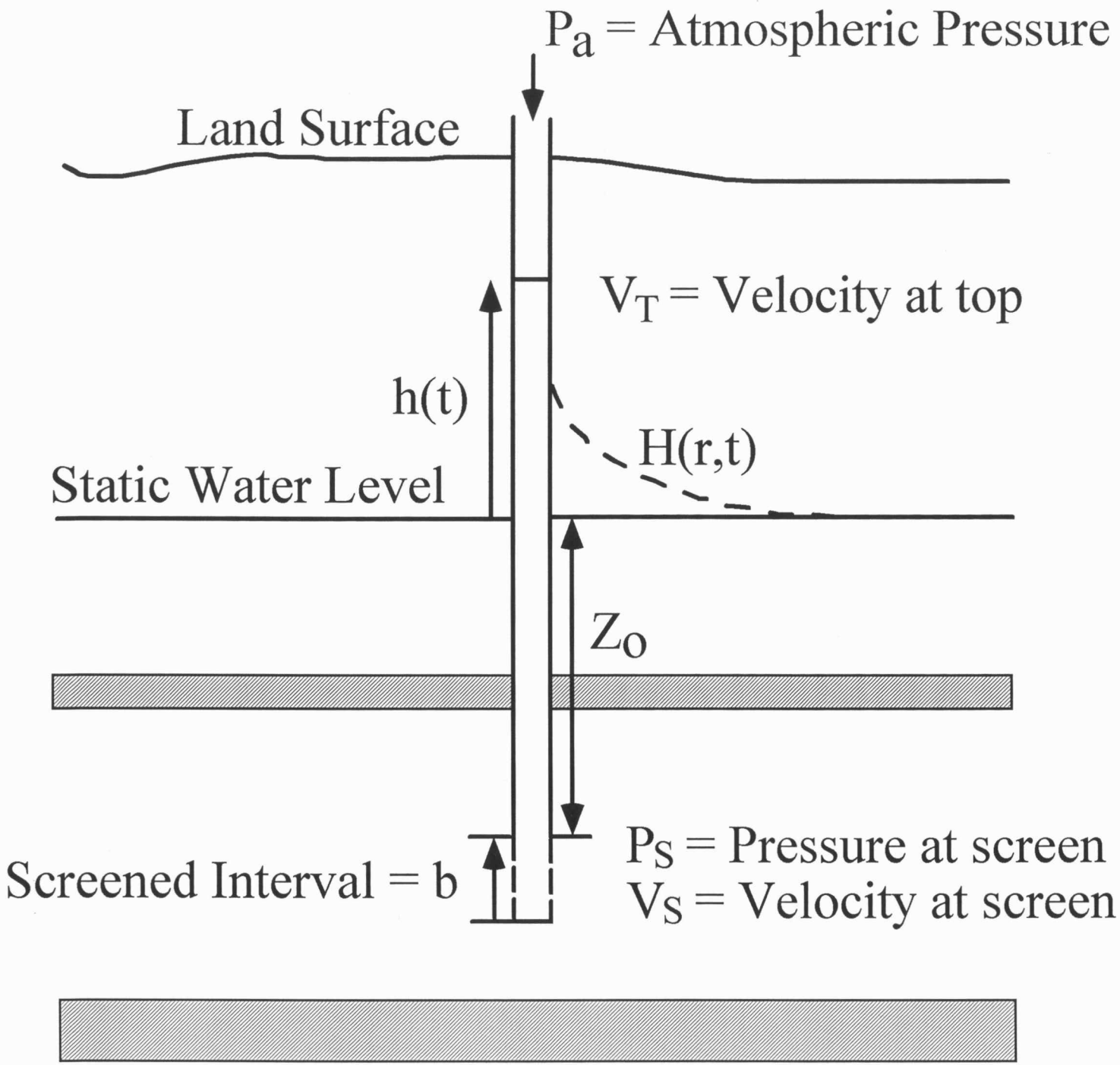
This paper will focus on the problems of doing slug tests in extremely permeable aquifers. We will show details of the field techniques that we use and provide examples of what to look for in the field data to indicate that conventional theories are inappropriate for analysis. The ultimate objective of this research is to develop and improve field and analysis techniques for better definition of the spatial distribution of hydraulic conductivity in high permeability environments.

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

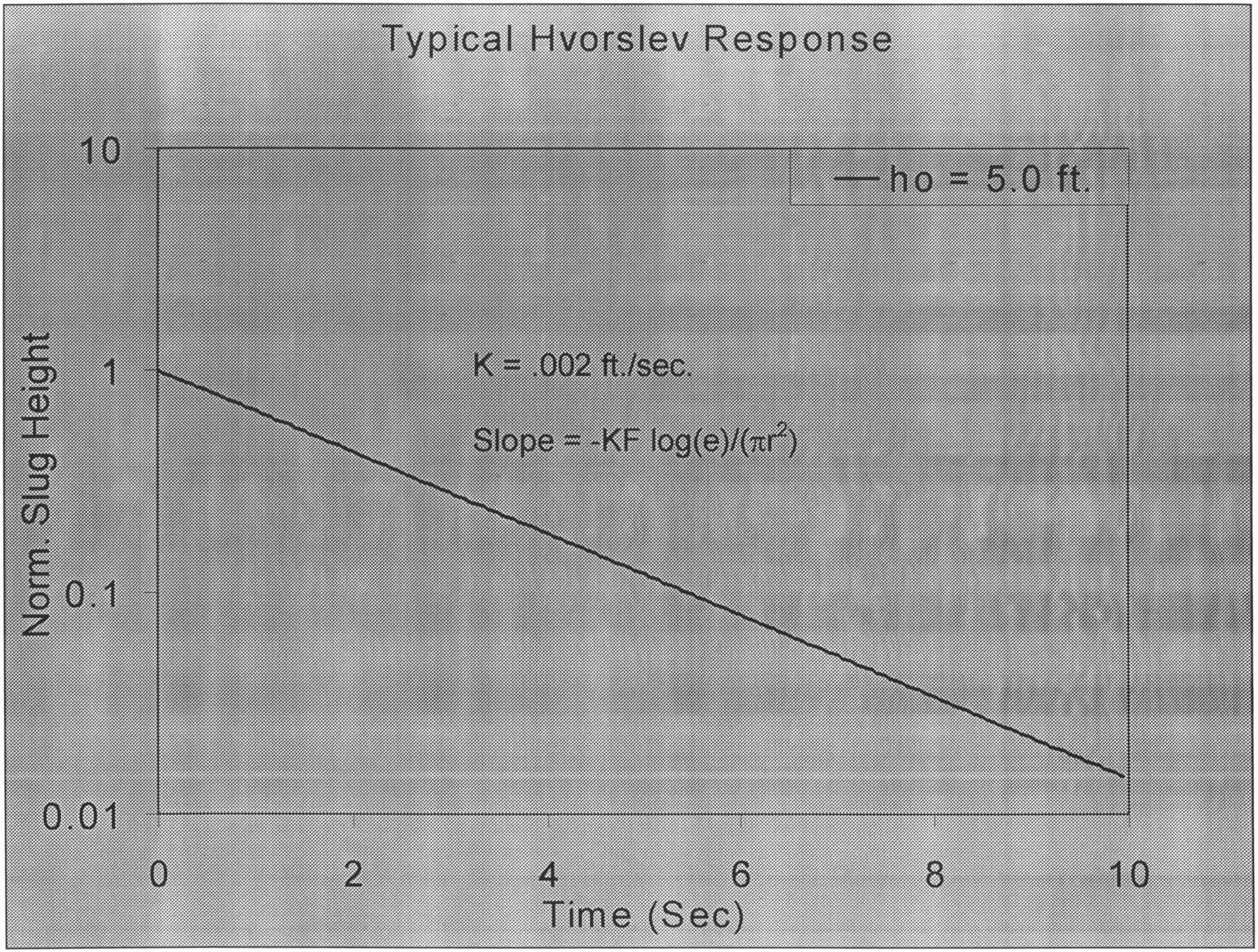
Typical Slug Test Arrangement

- 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_o is the length of water below the static level to the top of the screen
- b is the length of the screen


P_a = Atmospheric Pressure
Land Surface
V_T = Velocity at top
h(t)
H(r,t)
Static Water Level
Z_o
P_S = Pressure at screen
V_S = Velocity at screen
Screened Interval = b

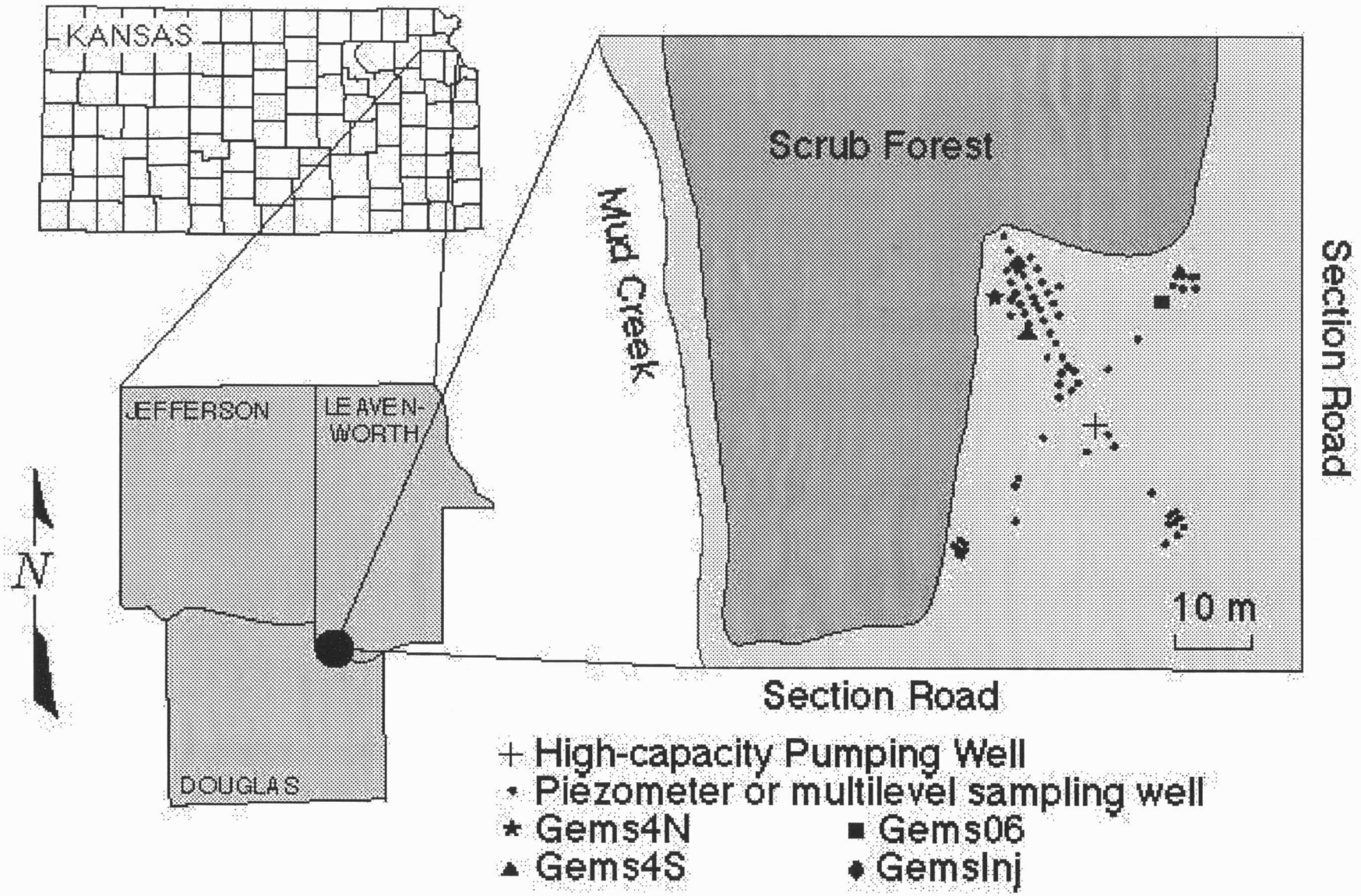
Linear Slug Test Models

- 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
10
1
0.1
0.01
Norm. Slug Height
—ho = 5.0 ft.
K = .002 ft./sec.
Slope = -KF log(e)/(πr²)
0
2
4
6
8
10
Time (Sec)

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

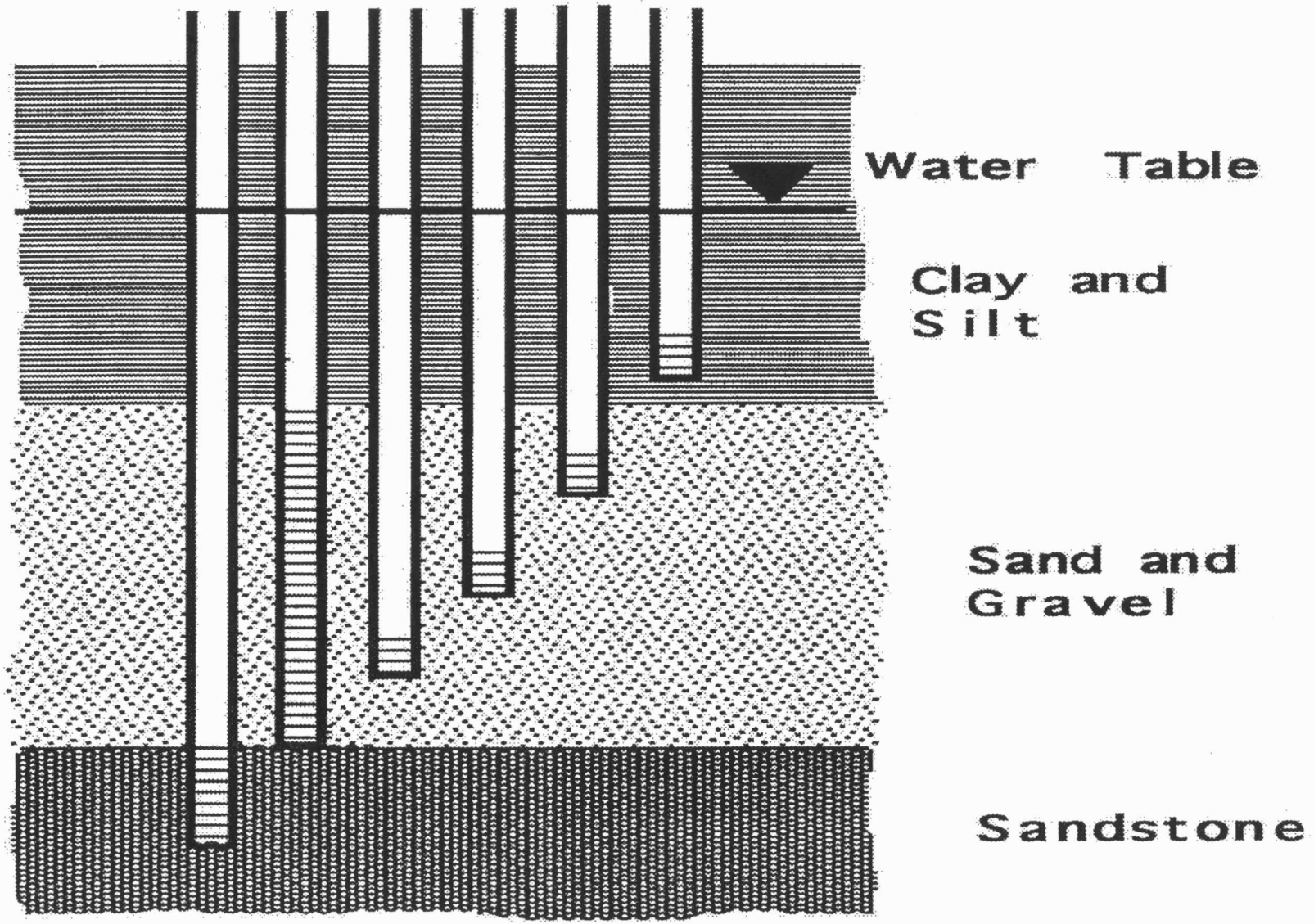


Location map for the Geohydrologic Experimental and Monitoring Site (GEMS).

Well Nests at GEMS

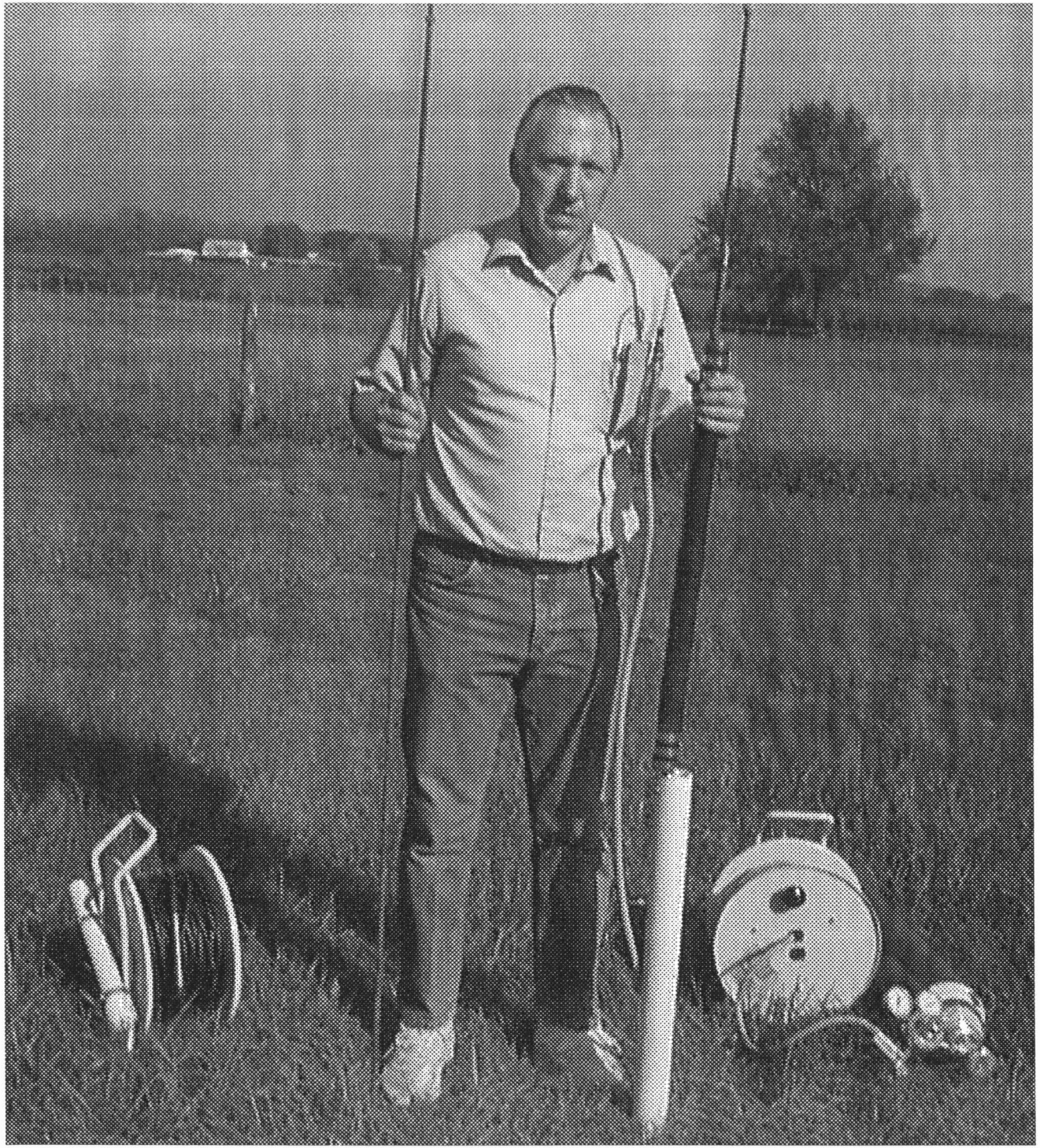
- A typical well nest is shown in the next slide. Typically there is a fully screened well and several wells with short screens completed at various depths. In some nests we may have a well completed into the bedrock.

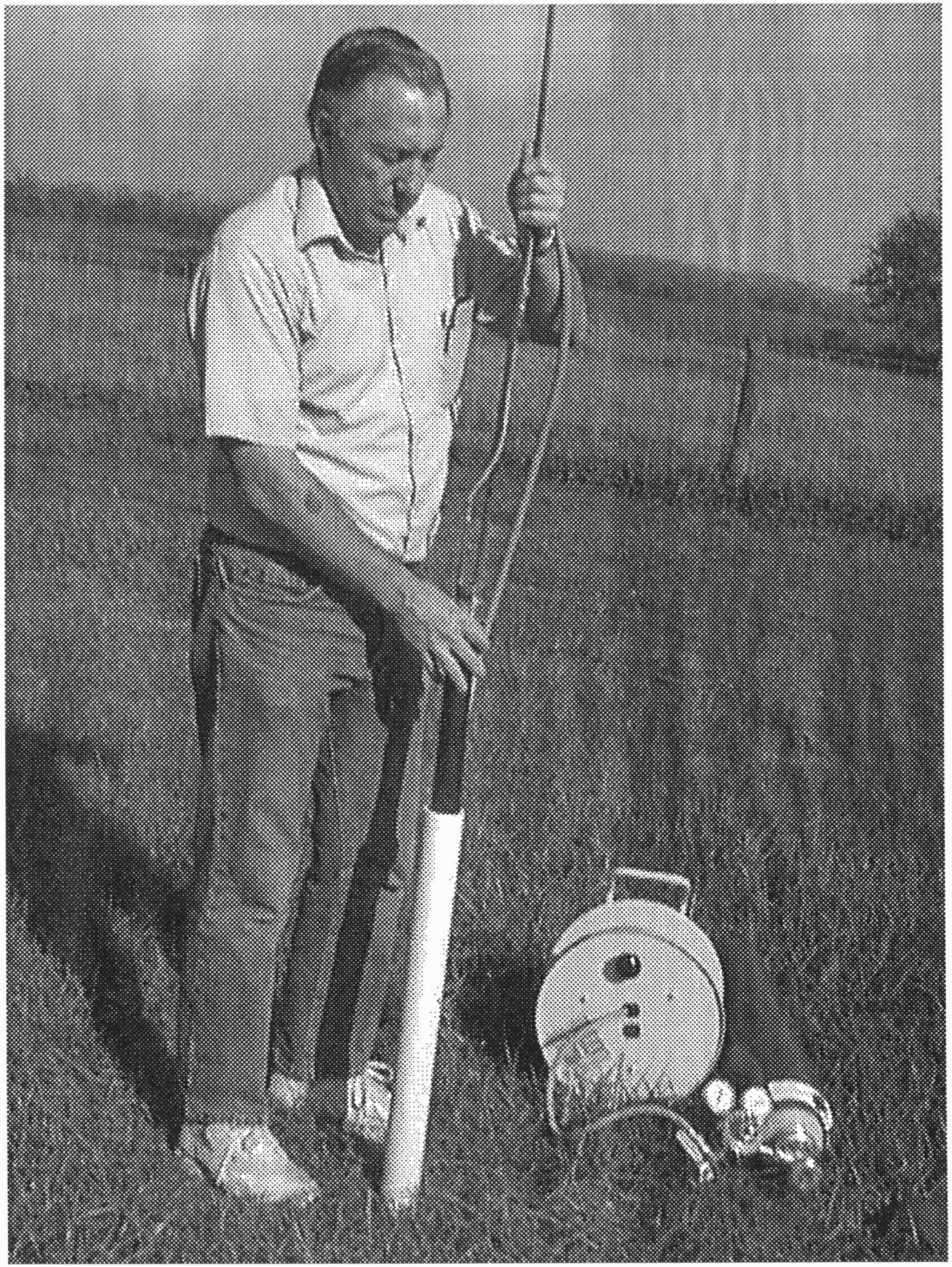
Typical GEMS Well Nest

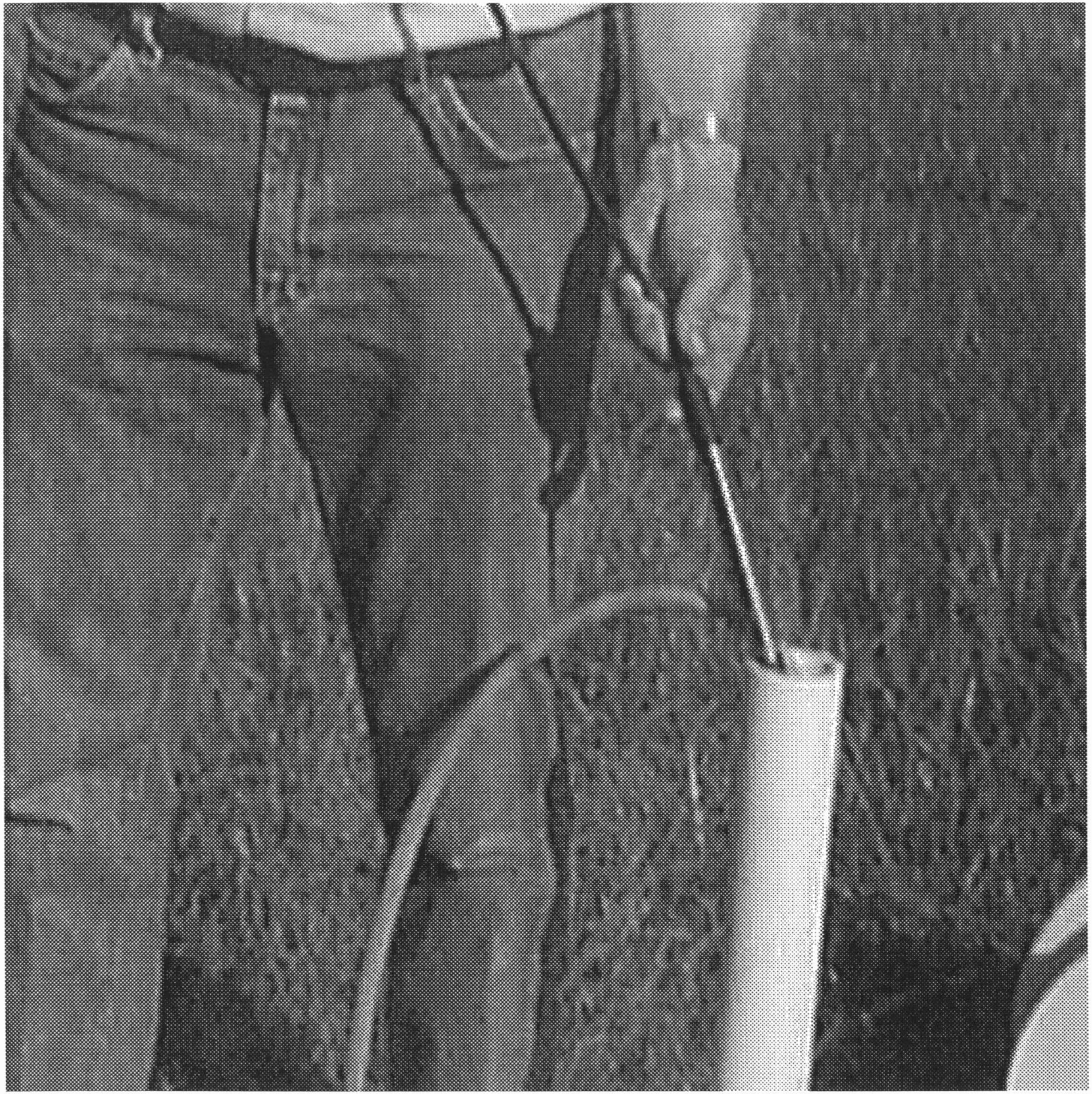


Slug-Test Equipment

- 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

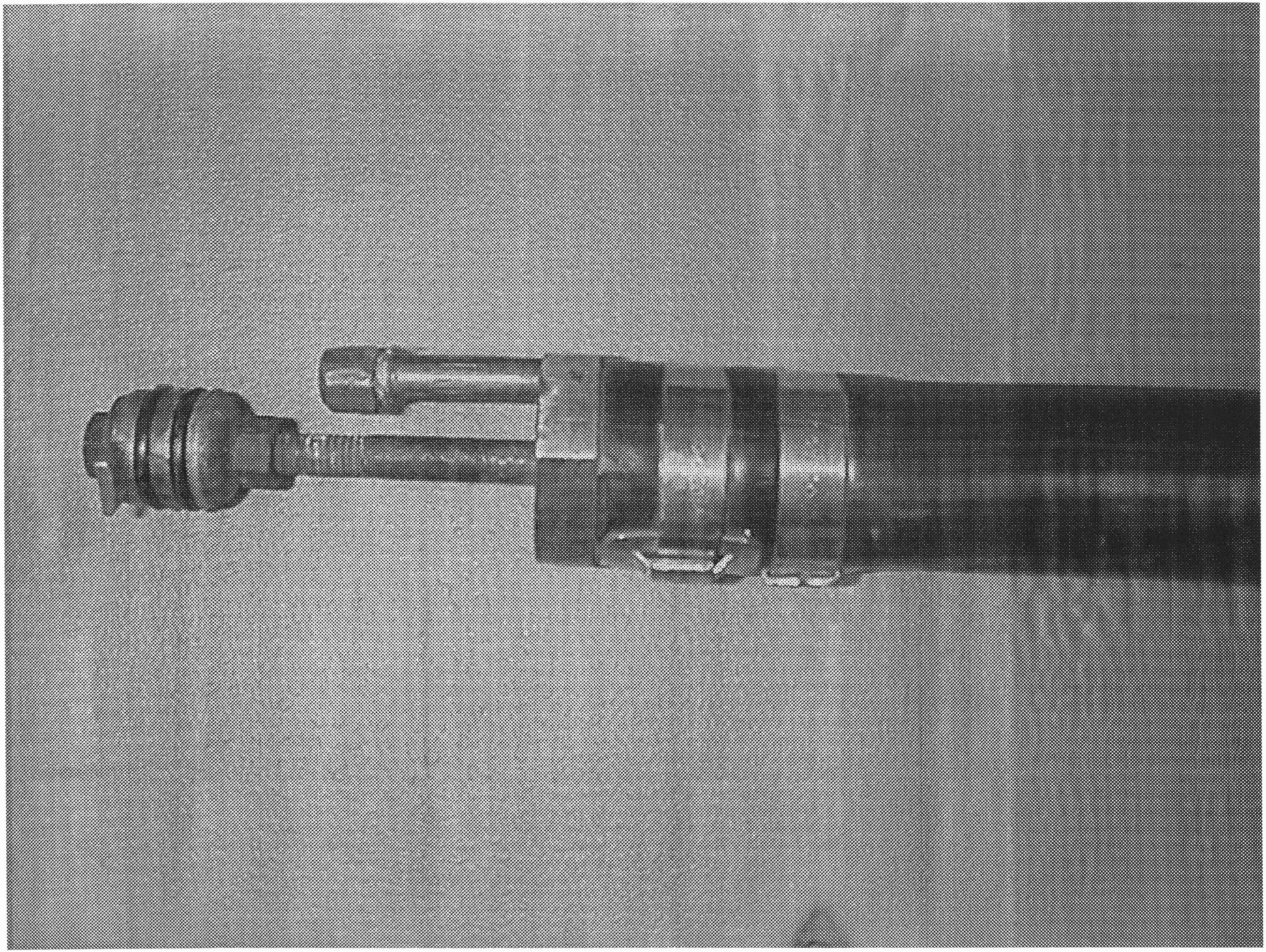


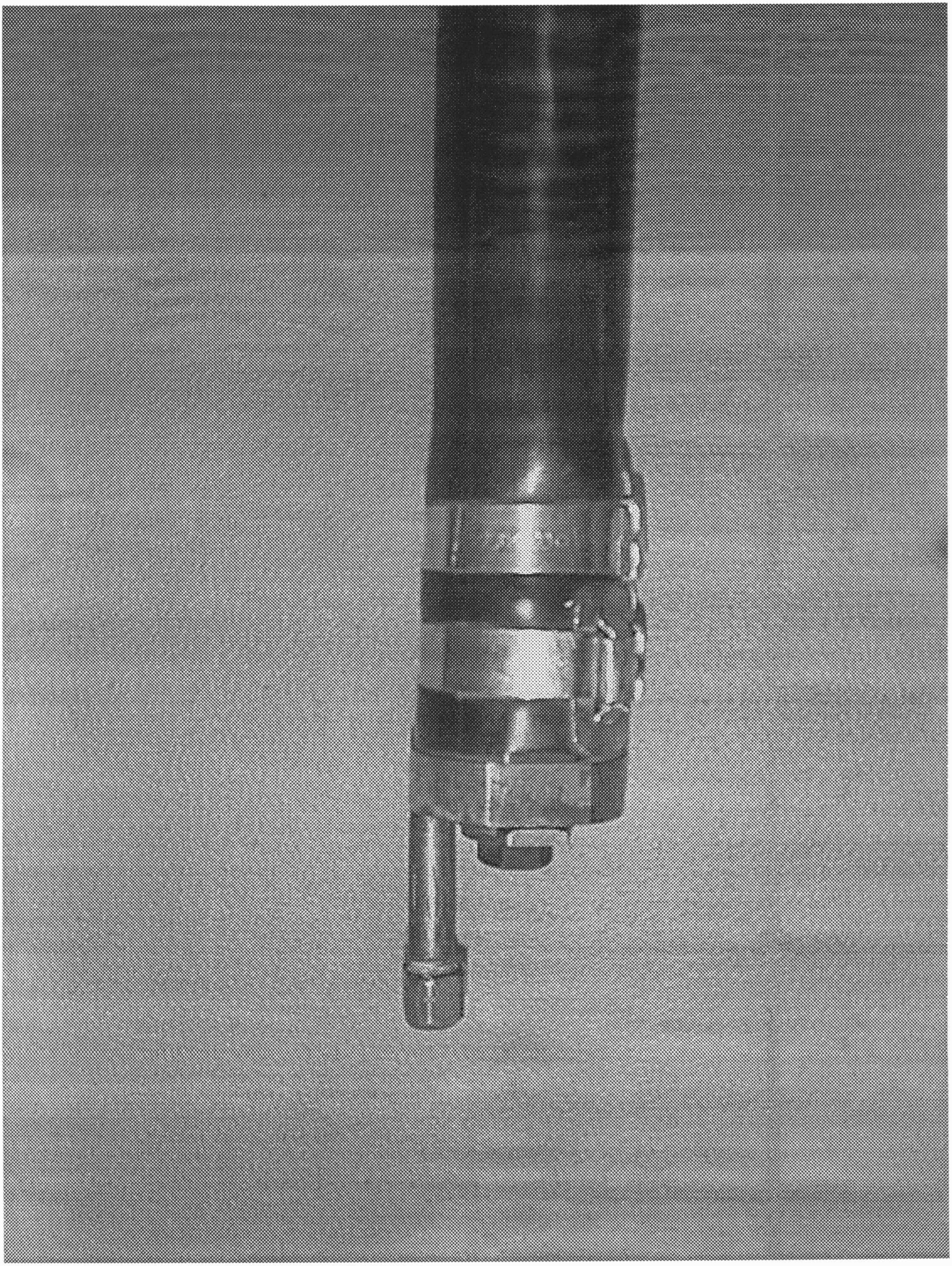




Instigation of Slug Test

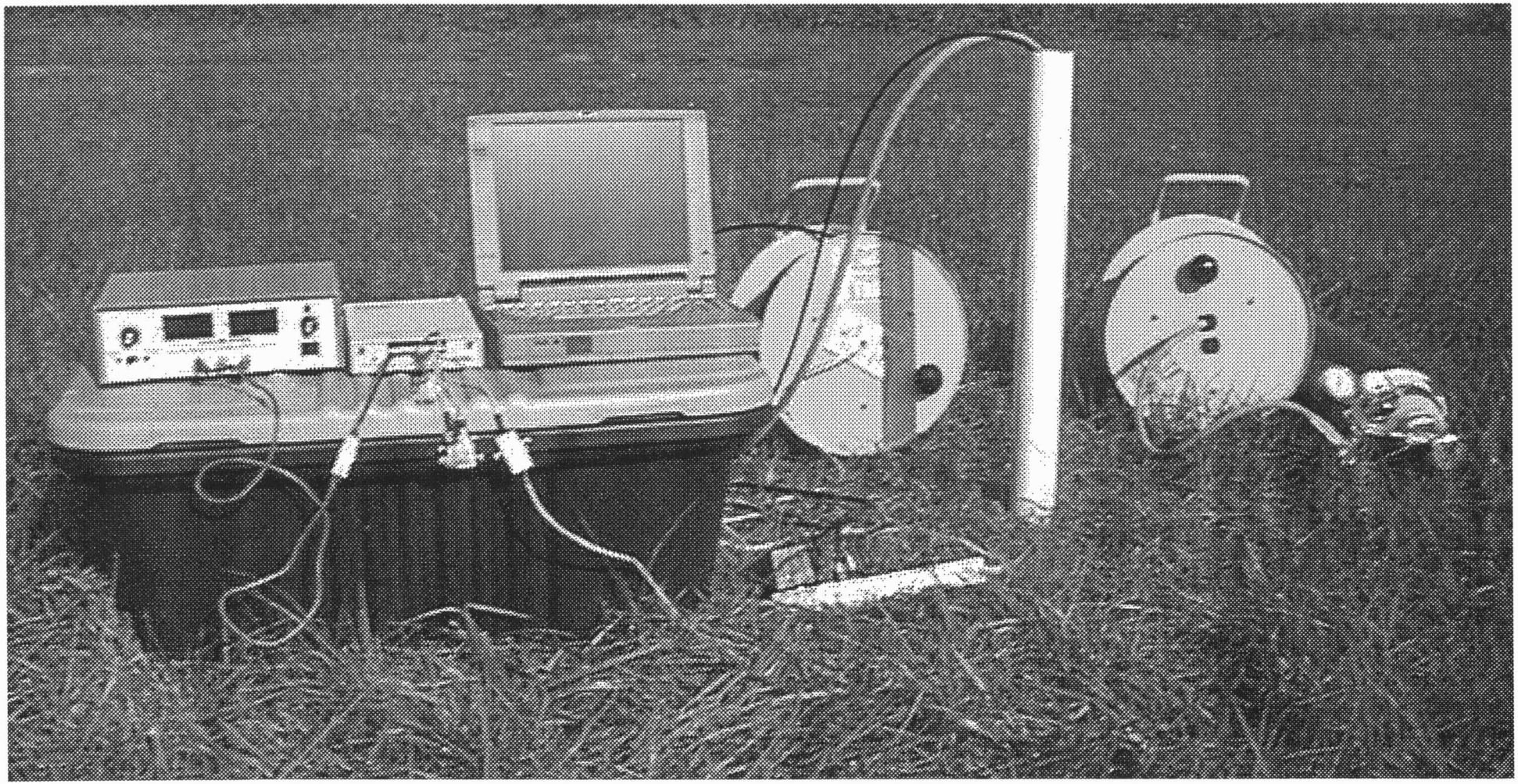
- There is a piston on the end of the pump rods.
- The pump rods may be moved to open and close throat of the packer.
- The packer is closed and water is added.
- When the piston is lowered the slug test is instigated.





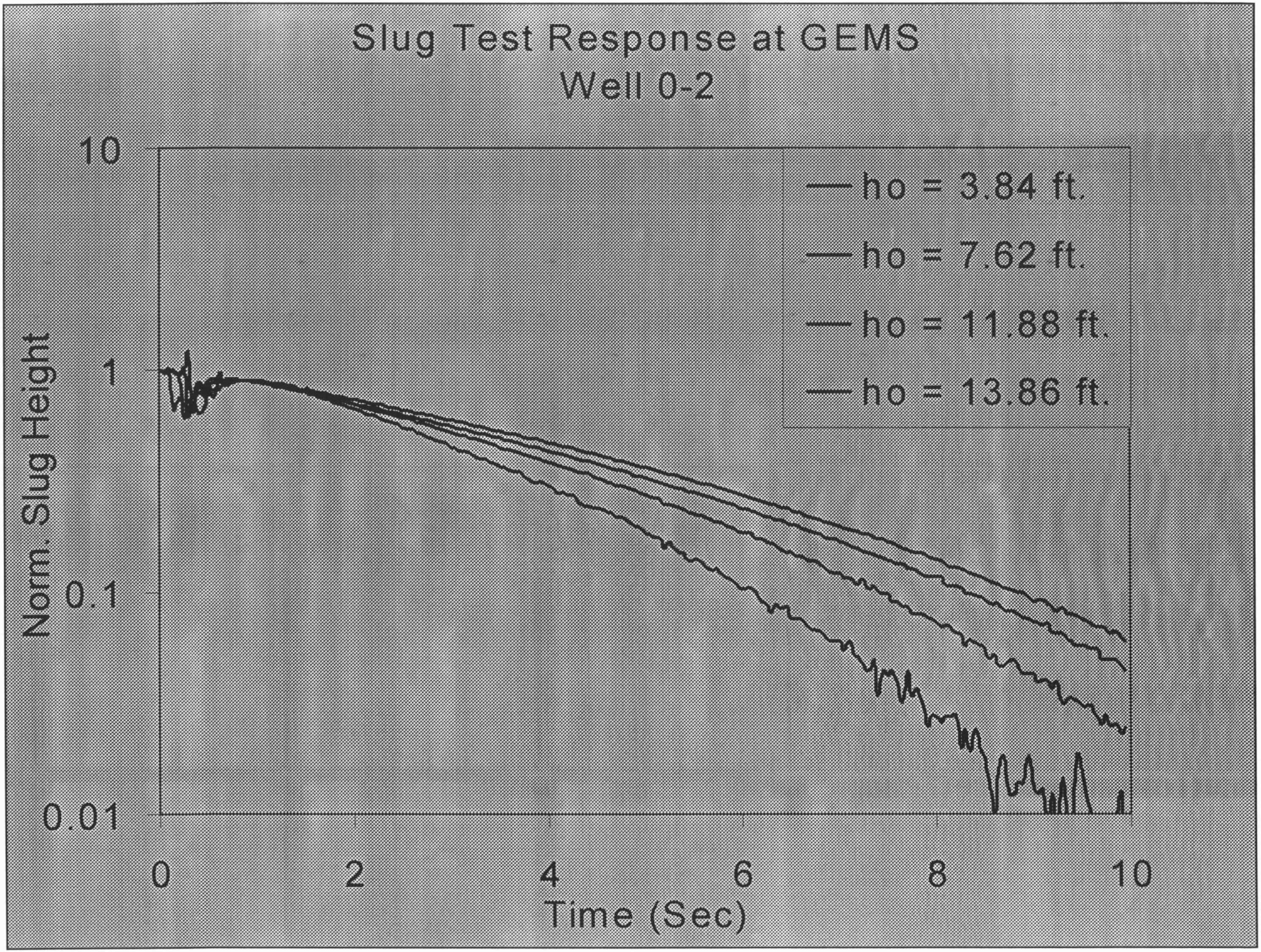
Recording of Slug-Test Data

- 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.



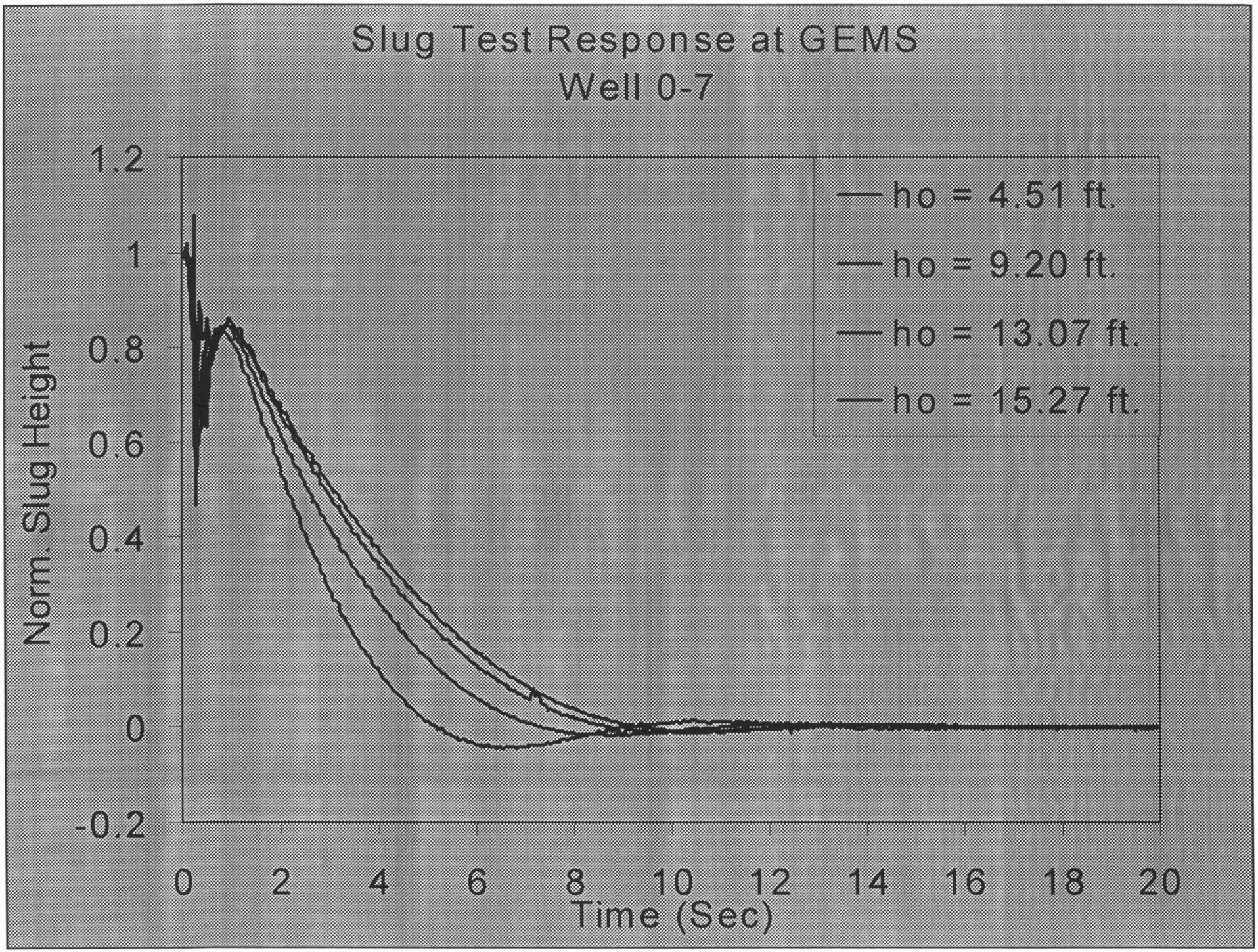
Slug Tests at GEMS

- 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
10
1
0.1
0.01
Norm. Slug Height
ho = 3.84 ft.
ho = 7.62 ft.
ho = 11.88 ft.
ho = 13.86 ft.
0
2
4
6
8
10
Time (Sec)

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
Norm. Slug Height
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
2
4
6
8
10
12
14
16
18
20
Time (Sec)
ho = 4.51 ft.
ho = 9.20 ft.
ho = 13.07 ft.
ho = 15.27 ft.

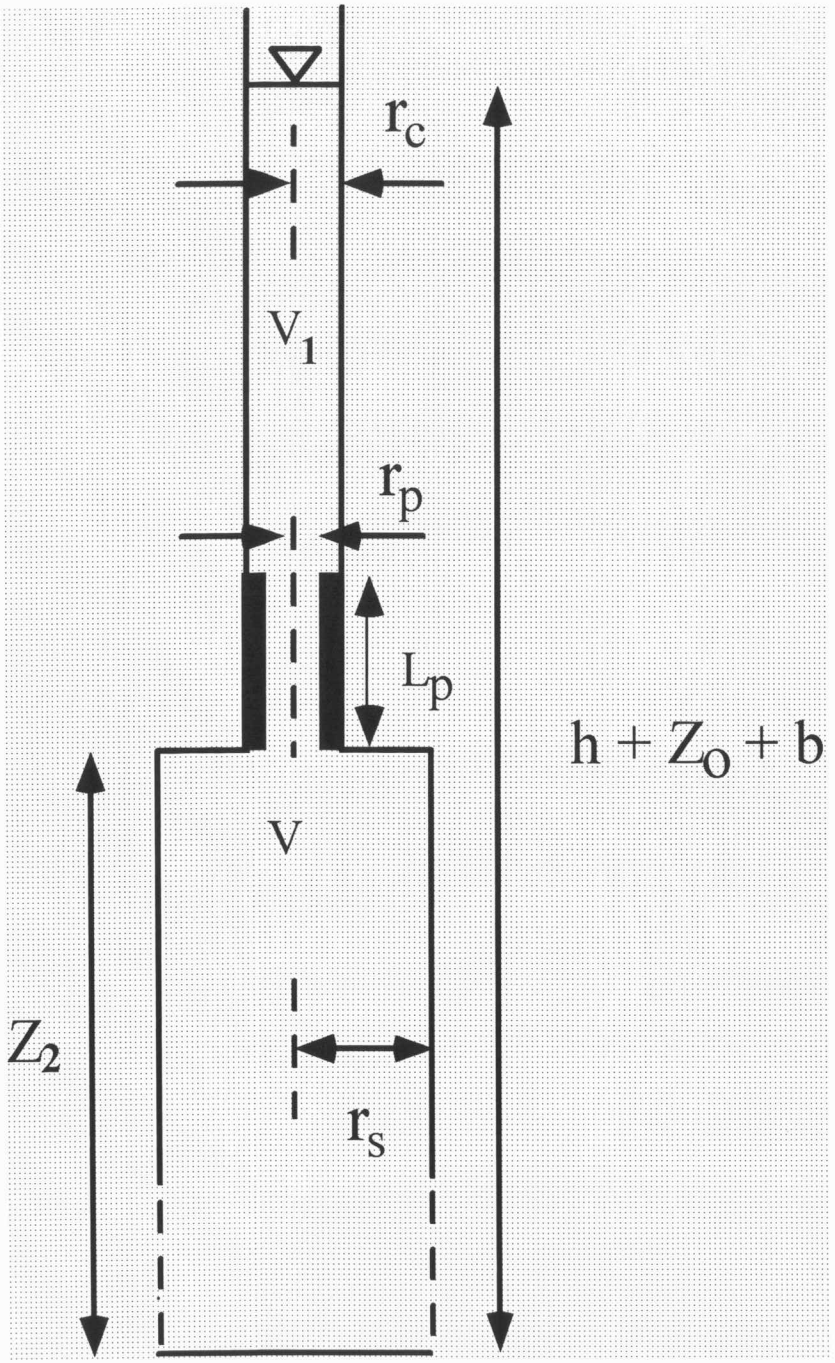
The General Nonlinear Model

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

- 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

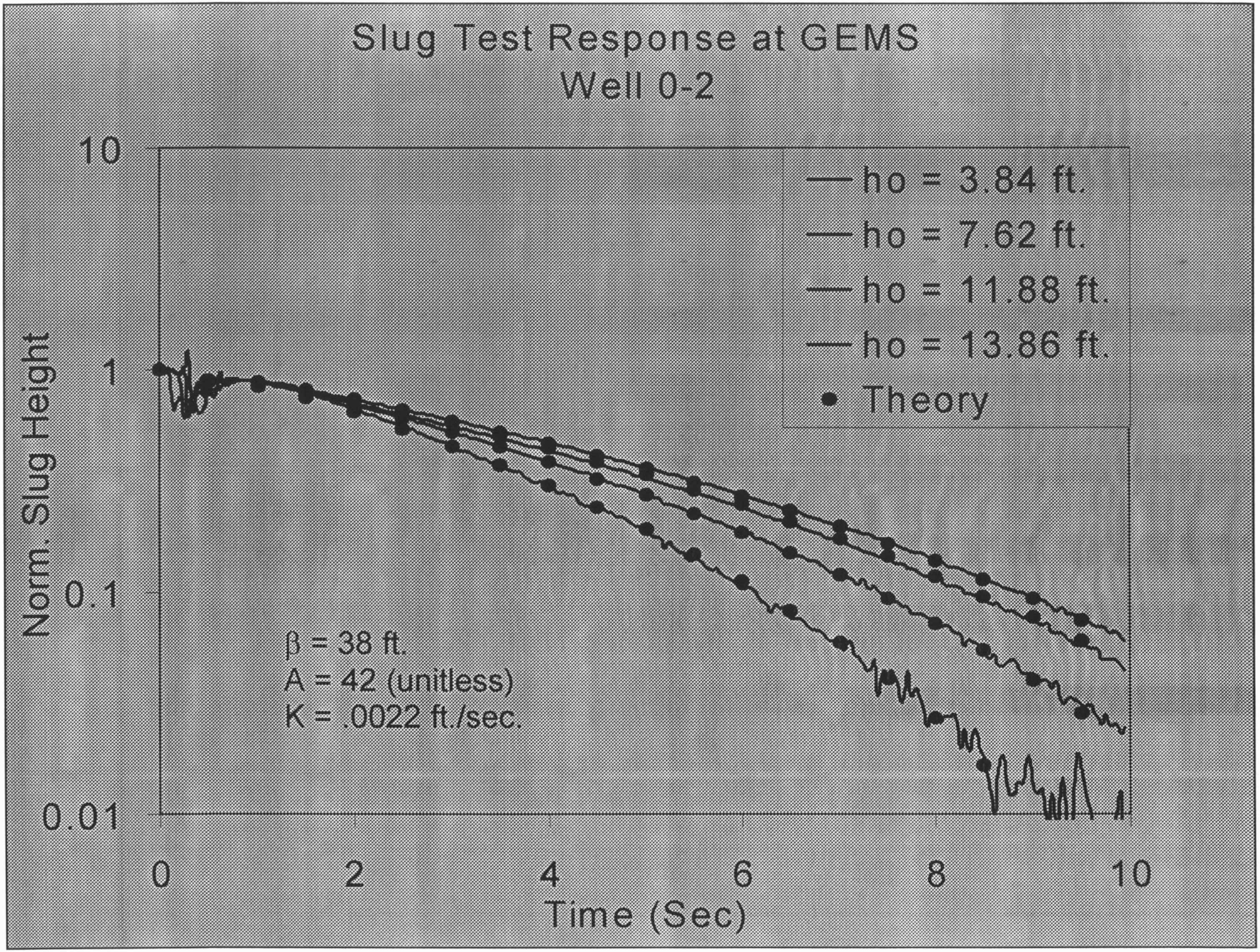
- Radius change due to packer
- Radius change due to casing diameter change

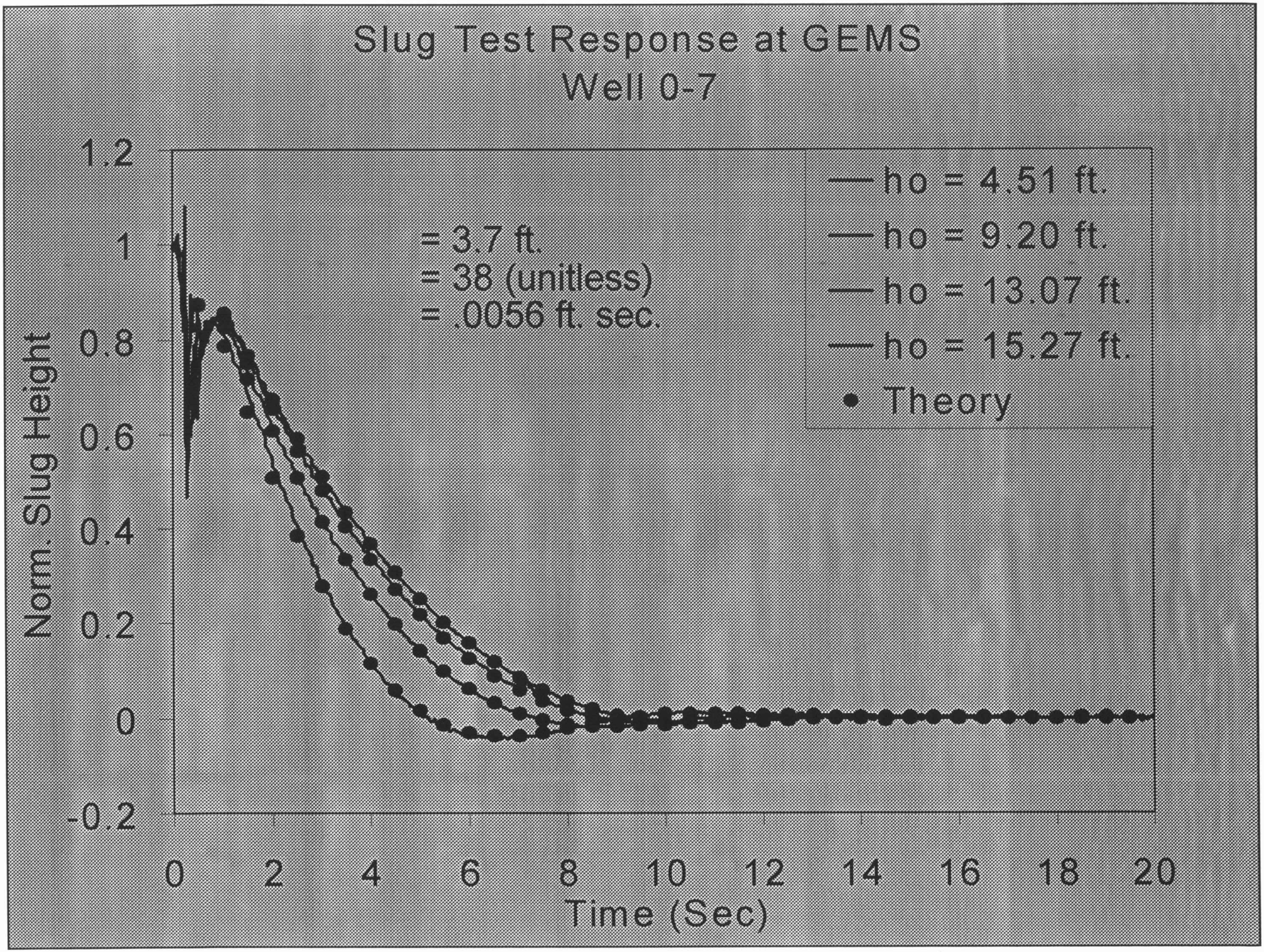


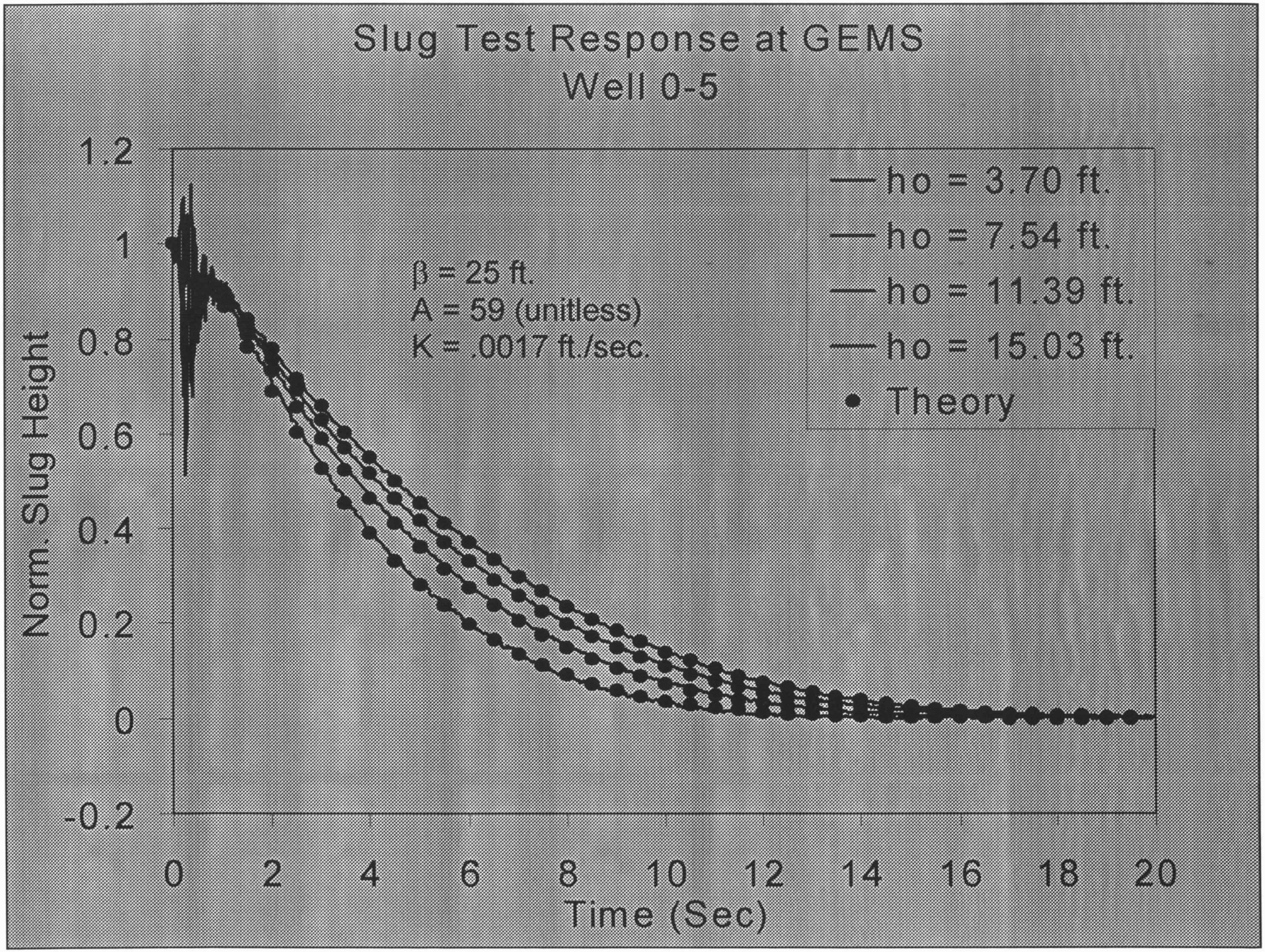
Typical Slug-Test Wellbore with Packer

Fit of Nonlinear Model to Data

- The nonlinear model has three parameters (b, 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
10
1
0.1
0.01
Norm. Slug Height
ho = 3.84 ft.
ho = 7.62 ft.
ho = 11.88 ft.
ho = 13.86 ft.
Theory
β = 38 ft.
A = 42 (unitless)
K = .0022 ft./sec.
0
2
4
6
8
10
Time (Sec)


Slug Test Response at GEMS
Well 0-7
= 3.7 ft.
= 38 (unitless)
= .0056 ft. sec.
ho = 4.51 ft.
ho = 9.20 ft.
ho = 13.07 ft.
ho = 15.27 ft.
Theory
Norm. Slug Height
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
2
4
6
8
10
12
14
16
18
20
Time (Sec)


Slug Test Response at GEMS
Well 0-5
β = 25 ft.
A = 59 (unitless)
K = .0017 ft./sec.
ho = 3.70 ft.
ho = 7.54 ft.
ho = 11.39 ft.
ho = 15.03 ft.
Theory
Norm. Slug Height
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
2
4
6
8
10
12
14
16
18
20
Time (Sec)

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

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.